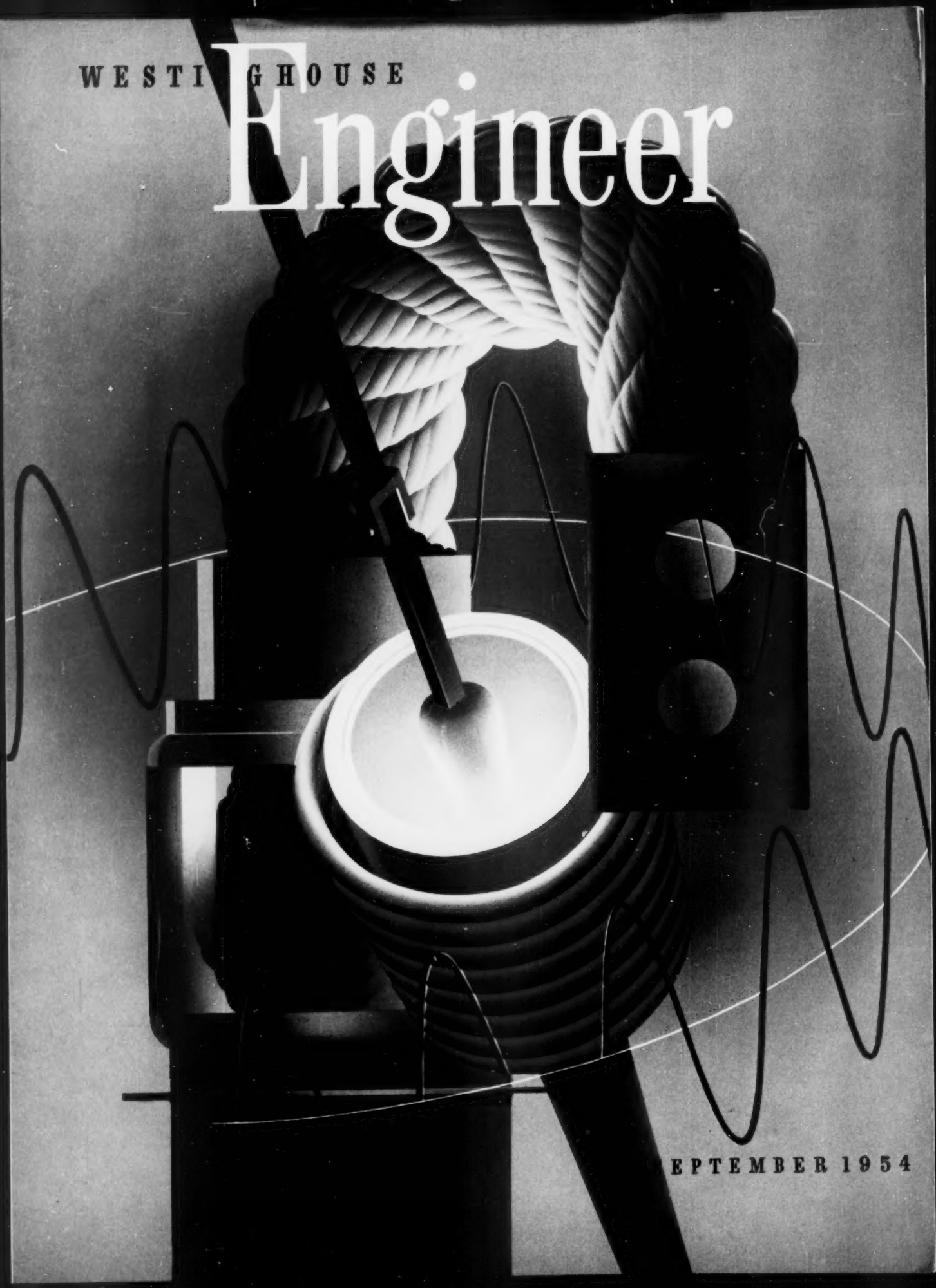
WESTINGHOUSE

Engineer



SEPTEMBER 1954

for the Future

For Your Convenience

This slip is a routing list, which may be used in sending this issue of WESTINGHOUSE ENGINEER to other members of your staff who should read it.

DO NOT TEAR OFF

Simply fold the slip upward and around the top of the front cover. The routing form then appears at the front and is ready for use.

e prediction of our fu-
nd sources, for even 50
would be a precarious
on seems to be entering
d between what have
entional energy sources,
of previously untapped
els, on which we have
r centuries, are playing
how fast is anyone's
r coal depletion, for ex-
50 years up to eight or

business of making or
hat harnesses energy—
arly everyone—need to
to the future sources
ne serious thought. Our
ubled since 1900; and
ward on a steep curve.
living likewise is still
pace. These two factors
rse, mean that energy
g even faster.
graph at left, energy
creasing by leaps and
at the present rate of
nly about 50 years we
energy as was used in
sly. And projecting the
crease, we may well be
as much energy an-
nually in 50 years as we do today; and by 2050—not very far away—perhaps five to ten energy units (one energy unit equals 10^{18} Btu) a year. These "guesstimates" are based on what appear to be the most reliable sources; but even if you halve them, the total energy requirement is nothing short of startling.

The amount of fuel available to satisfy this expected demand is subject to considerable difference of opinion. This revolves not only about the actual amount of fuel material left in the earth, but more important, about the amount that can feasibly and economically be recovered. No one *knows*. Considering what appear to be the most careful evaluations, it seems abundantly clear that we must give greater attention to our energy resources.

The methods seem obvious—develop ways to use the virtually untouched energy sources, such as the atom and the sun, and utilize our present sources as carefully and as efficiently as possible. Strides are being made toward both goals.

As is outlined elsewhere in this issue, work on a nuclear-power plant of central-station size is well under way. And nuclear reactors of many different types are being subjected to intensive study to find the best ways of harnessing nuclear power. But the country is still in the early stages of developing new energy sources, so we must also look to our present uses, and be more thrifty of our present fuels.

Regardless of nuclear developments, it seems likely that the turbine and the generator will be our primary method of developing electric power for an indefinite period. Some significant advances have been made in both of these basic equipments. A decade ago, turbine generators seemed to be approaching the limiting point in size. They had reached the maximum speed usable to supply 60-cycle power. Rotors had approached the point where the strength and size of forgings prevented any increase in diameter. The previous technique of increasing capacity by raising hydrogen pressure could no longer be used.

Then the technique of inner cooling of generator windings was developed. The benefits derived make it possible approximately to double the amount of load that can be carried by a given machine. This, coupled with other recent developments, such as Thermalastic insulation and a Magamp excitation and regulation system, provide more reliable, efficient, and economical machines.

Turbines can also be further improved. Steam pressures may reach 7500 pounds. Temperatures will pass 1300 degrees. As much as 500 000 kw on a single shaft is highly probable.

Such improvements in turbine generators are important not only in the short-range future of the next decade, but also in the longer view; as yet no way has been found to convert nuclear energy directly to usable blocks of electric power, so nuclear reactors will serve primarily as a heat source.

As we are awakening to our growing depletion of conventional fuel sources, we are taking some definite steps. But time may be shorter than we think. Much more effort must be expended in investigating untouched energy sources, such as the sun, and in more carefully utilizing conventional fuels.

RWD

WESTINGHOUSE Engineer

VOLUME FOURTEEN SEPTEMBER, 1954 NUMBER FIVE

On the Side

The Cover—To a greater degree than in most devices, the success of a practical semiconductor rectifier depends upon the precision with which the constituent materials are prepared. For example, the new germanium Semitron rectifier, shown in the background of the cover, would not be possible without the large, carefully grown, germanium single crystals from which the rectifying portion of the device is made. Therefore, artist Dick Marsh has appropriately chosen to portray the crystal-pulling operation as well as the rectifier itself.

• • •

Microwave communication is being installed on a 200-mile Standard Oil Company (Indiana) pipeline.

The initial installation will provide remote control of three outlying very-high-frequency radio stations. The microwave equipment can be expanded to feature 30 simultaneously usable channels. Three will be used for voice communications, and 27 will be available for additional voice service, telegraph or teletype, or remote control of valves, motors, and other operations of the pipeline.

• • •

A new "indoor proving ground" for transformers will soon be under construction at the Westinghouse Transformer Division. Included in the new facilities will be a large sound laboratory, capable of testing transformers weighing up to 400 tons and rated at over 500 mva—much larger than any transformers now being manufactured. Other facilities will include high-voltage, high-current test areas.

In This Issue

THE PHYSICS OF NUCLEAR POWER 162
W. E. Shoupp

THE PWR SYSTEM—SOME FACTS AND FIGURES 173
C. H. Weaver

AN ENGINEERING PERSONALITY—JOHN L. BOYER 174

FROM TRONA TO SODA ASH 176

SEMICONDUCTORS—CHARACTERISTICS AND PRINCIPLES 178
T. R. Lawson, Jr.

SEMICONDUCTOR MANUFACTURE 182

POWER RECTIFICATION VIA GERMANIUM AND SILICON 183
John L. Boyer

TRANSFORMER INSULATION 187
W. L. Teague and L. B. Rademacher

WHAT'S NEW 192
New tandem steel mill—Transistorized power-line carrier—Leak-tight vacuum valve—Harder marine gears—Radio-shielded laboratory.

The following terms, which appear in this issue, are trademarks of the Westinghouse Electric Corporation and its subsidiaries:

Fosterite, Hisercap, Inerteen, Kovar, Life-Line Lowgrocap, Magamp, Micarta, Semitron, Thermalastic.

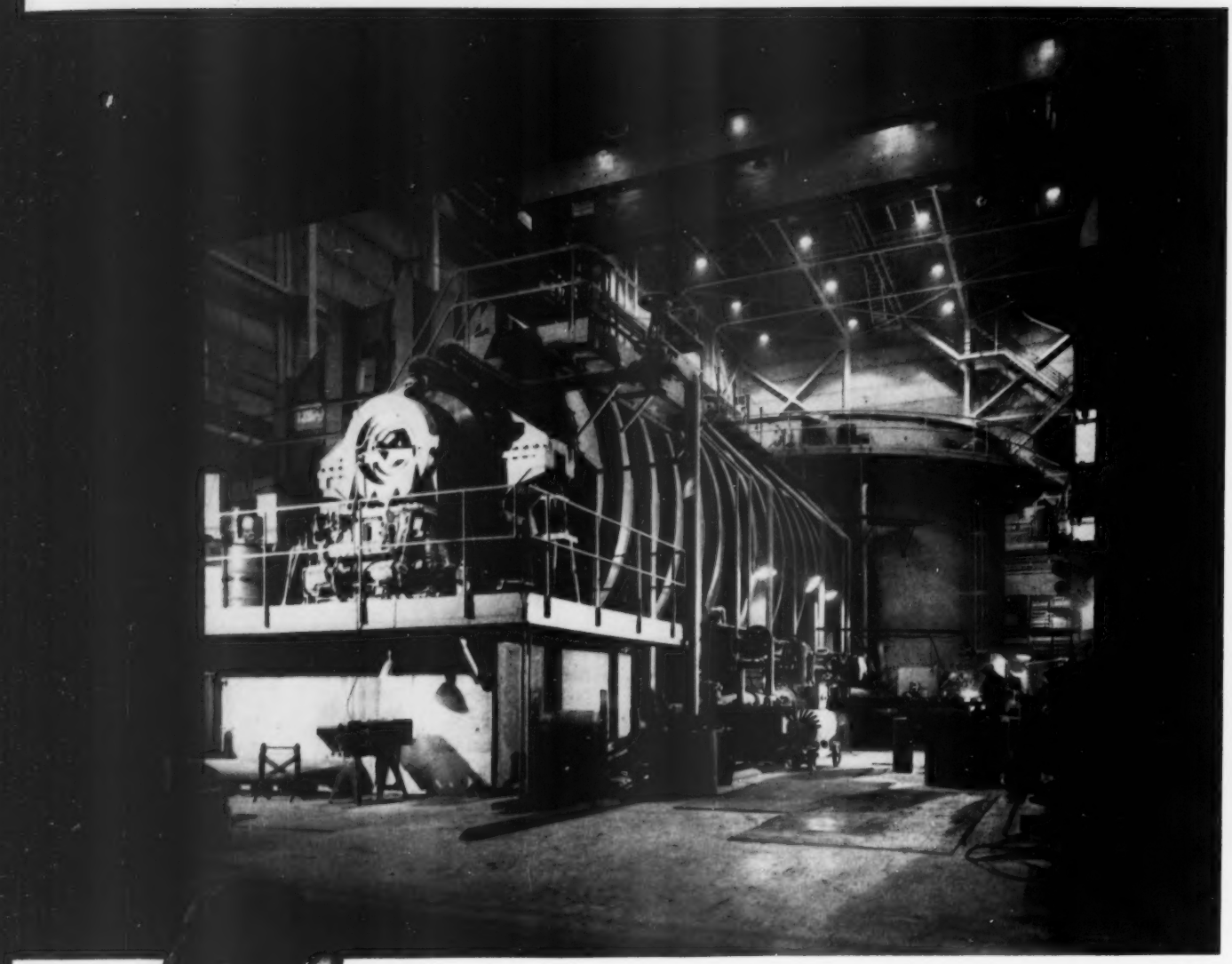
Editor ..... CHARLES A. SCARLOTT
Managing Editor .... RICHARD W. DODGE
Assistant Editor ..... M. M. MATTHEWS
Layout and Production ... EMMA WEAVER
Editorial Advisors A. C. MONTEITH, J. H. JEWELL, DALE MCFEATTERS

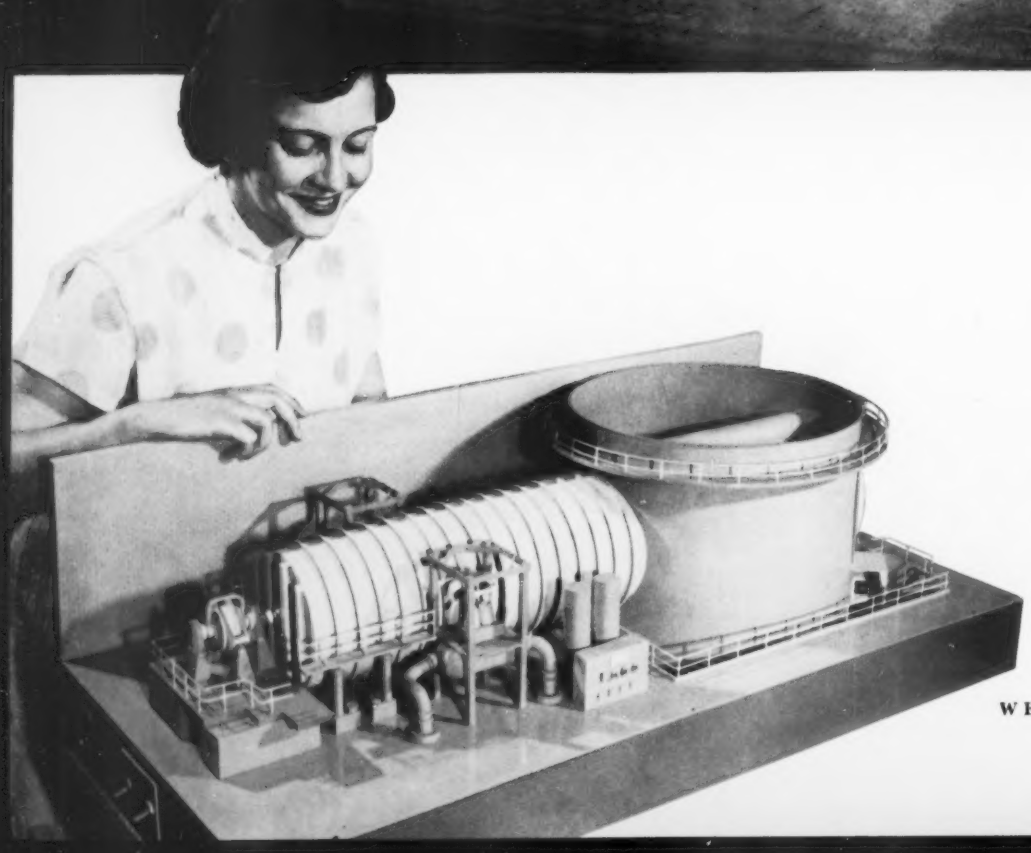
Published bimonthly (January, March, May, July, September, and November) by the Westinghouse Electric Corporation, Pittsburgh, Pa.

Subscriptions: Annual subscription price in the United States and possessions is $2.50; in Canada, $3.00; other countries, $3.00. Single copy, 50¢. Address all communications to *Westinghouse* ENGINEER, P. O. Box 2278, 401 Liberty Ave., Pittsburgh 30, Pa.

Indexing and Microfilm: *Westinghouse* ENGINEER contents are regularly indexed in Industrial Arts Index. Reproductions of the magazine by years are available on positive microfilm from University Microfilms, 313 N. First Street, Ann Arbor, Michigan.

THE WESTINGHOUSE ENGINEER IS PRINTED IN THE UNITED STATES BY THE LAKESIDE PRESS, CHICAGO, ILLINOIS





Located inside a large windowless building at the National Reactor Testing Station in the Idaho desert is this prototype of the nuclear power plant for the U.S.S. *Nautilus*. The above view through the door of the building shows the hull section, and the sea tank; on the near end of the hull is the water brake, which absorbs power developed by the Mark I. At left is a model of the submarine hull section and the sea tank.

NUCLEAR POWER
the physics of

Nuclear physics was once a topic discussed only in the classroom or research laboratory. Fission, fusion, mass number, chain reaction—these were strange words to all but scientists. But with the advent of the atom bomb, and now a nuclear power plant, nuclear physics has become a significant subject to the whole technical world. Fortunately, a "speaking acquaintance" with the nuclear facts of life is not too difficult to obtain.

DR. W. E. SHOUPP, *Assistant Manager, Atomic Power Division, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania*

THE ATOMIC BOMB, among other things, catapulted Einstein's mass-energy relationship into the engineer's world. All of the accustomed heat reactions are of the chemical type, characterized by the interplay of electrons in the outer orbits of combining and disassociating atoms, with the nuclei of these atoms remaining aloof. Now comes a vastly different sort of reaction, with a heat release greater by a million times. In this the atomic nucleus is involved—and with it all phases of engineering.

Nuclear reactions, which deal with changes in the atomic nucleus itself, have many of the same characteristics as chemical reactions, which involve changes in the outermost of the electrons that revolve planet-like about the nucleus. In fact, nuclear reactions are written much the same as chemical reactions, except that the symbols for elements or compounds are replaced by those for nuclei or subatomic particles. For example, compare the following two reactions, the first being the common chemical reaction of combustion, and the second a nuclear step in the sequence that describes the origin of solar energy:

$$C+O_2 \rightarrow CO_2 \qquad (1)$$

$${}_7N^{15}+{}_1H^1 \rightarrow {}_6C^{12}+{}_2He^4 \qquad (2)$$

The first reaction states that one atom of carbon (coal) unites with two atoms of oxygen to form one molecule of carbon dioxide. The subscripts indicate the relative number of atoms taking part in the reaction.

The second reaction states that a nitrogen nucleus bombarded by a proton (hydrogen nucleus) absorbs the proton and emits an alpha-particle (helium nucleus), thereby forming a carbon nucleus (see Fig. 1). Here a subscript denotes the number of protons in the nucleus and, since the atom is a neutral entity, it also indicates the number of orbital electrons. The number of electrons determines the atom's chemical properties; atoms with the same chemical properties are grouped into elements. Therefore, the number of protons in the nucleus of an element specifies the element and indicates its position in the periodic table of the elements. This number is termed the *atomic number* of the element. A superscript indicates the total number of protons and neutrons in the nucleus. Since protons and neutrons account for nearly all the weight of an atom and the weight of both is close to unity, the superscript is the integer nearest the atomic weight. This integer is called the *mass number*. The terms atomic number and mass number are illustrated in Fig. 2.

Nuclear reactions are, however, frequently written in another manner; for example, reaction (2) can be written in the following shorthand form:

$$N^{15}(p,\alpha)C^{12} \qquad (3)$$

Reactions (2) and (3) are identical; the information is merely conveyed in a different manner. Note that the subscript has been dropped; it merely specifies the element, and imparts no information not given by the letter symbol for the element. The incident projectile and the ejected lightweight particle are grouped together in parentheses: p denotes the incident proton and α the ejected alpha-particle. The part in parentheses (p,α) is ordinarily used to describe reactions of this same general type, which would be spoken of as a proton, alpha-particle reaction or simply as a p, α reaction.

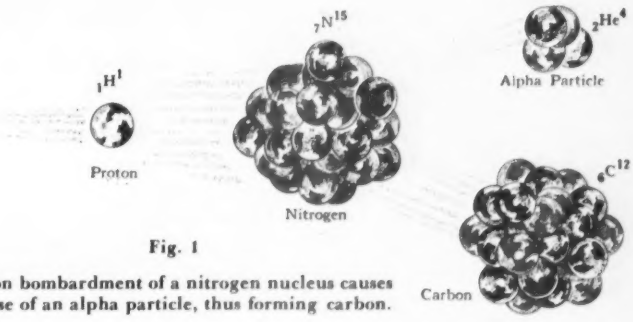


Fig. 1

Proton bombardment of a nitrogen nucleus causes release of an alpha particle, thus forming carbon.

Other symbols used in parentheses to describe nuclear reactions are for other atom-smashing projectiles and for other emitted particles. These include the neutron, designated by n; the deuteron, designated by d, which is a combined proton

and neutron forming the nucleus of one type of hydrogen ($_1H^2$); and the gamma-ray (or photon), designated by γ. Some of the other reactions are (n,p), (n,α), $(n,2n)$, (n,γ), (p,n), (p,d), (d,p), (d,n), (d,α), (α,p), (α,n), (α,np), (γ,n) and (γ,α). In the $(n,2n)$ reaction, the $2n$ indicates that two neutrons are ejected, and in the (α,np) reaction the np indicates that both a neutron and a proton are emitted.

Energy in Chemical Reactions

All energy used industrially comes either from the work done by falling water or from the combustion of fuels, principally coal and petroleum products. In the combustion of coal, carbon atoms combine with oxygen of the air to form carbon dioxide, with release of energy. The chief characteristic of ordinary combustion is that atoms involved in the process are not changed intrinsically. The carbon atom from coal is still a carbon atom in the CO_2 of the flue gas. The energy made available is chemical energy. In a chemical reaction, atoms of the same kind are present both before and after the reaction takes place.

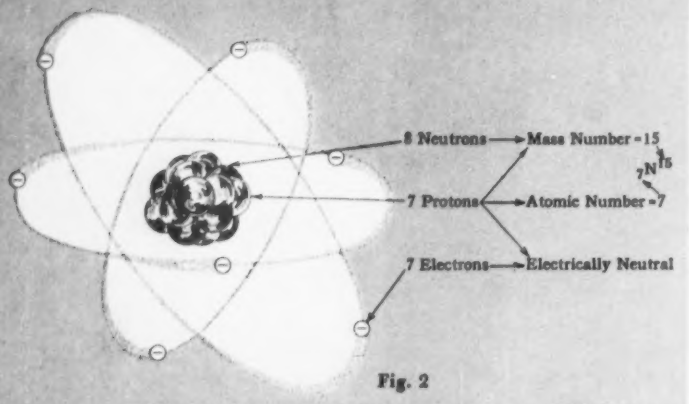


Fig. 2

This pictorial representation of a nitrogen atom illustrates the meaning and relationship of atomic and mass numbers.

Physicists express the energy released by nuclear reactions in terms of electron volts per atom transformed, an electron volt being the work done on an electron when it moves through a potential drop of one volt. An electron volt is 1.60×10^{-19} watt-second and is therefore a definite amount of energy, just as is a foot-pound of ordinary mechanical work. Chemists usually express energies of reaction in calories per mole of material transformed. (A mole is an amount in grams equal to the molecular weight of the substance in question and always contains 6.02×10^{23} molecules of the substance.) The heat of formation of CO_2 is about 94 000 calories per mole, that is, for formation of 6.02×10^{23} molecules of carbon dioxide. Because one calorie is 4.18 watt-seconds, the energy release accompanying the formation of one molecule of CO_2 is:

$$\frac{94\,000 \text{ cal}}{1 \text{ mole}} \times \frac{1 \text{ mole}}{6.02 \times 10^{23} \text{ molecules}} \times \frac{4.18 \text{ watt-sec}}{1 \text{ cal}} \times \frac{1 \text{ ev}}{1.60 \times 10^{-19} \text{ watt-sec}} = 4.1 \text{ electron volts} \quad (4)$$

To form a kilowatthour of energy by burning coal requires about one-fourth pound at 100-percent efficiency of conversion from heat to electrical energy.

Energy in Nuclear Reactions

In some chemical reactions, the addition of heat or energy is required before the reaction will proceed, while in others, such as combustion, energy is liberated. Precisely the same condition exists in nuclear reactions, and the terms endothermic and exothermic are similarly used to indicate whether energy is required or given off in the process. Like chemical equations, nuclear equations are more accurately represented by including a term Q to represent the energy of reaction, or "energy balance." Consequently, equation (2) should be written:

$$_7N^{15} + _1H^1 \rightarrow _6C^{12} + _2He^4 + Q \quad (5)$$

When the energy balance or Q value is positive, energy is emitted, i.e., the reaction is exothermic. When the energy balance is negative, energy is absorbed and the process is endothermic.

The magnitude of the energy balance is easy to compute if the masses of the reacting nuclei or atoms containing these nuclei are known. Consider, for example, the nuclear reaction caused by the bombardment of the metal beryllium ($_4Be^9$) with deuterons ($_1H^2$) accelerated in an atom smasher. In this reaction, the element boron is created and neutrons are emitted. This process, and the mass of each particle involved are as follows:

$$\begin{gathered} _4Be^9 + _1H^2 \rightarrow _5B^{10} + _0n^1 + Q \\ 9.01510 + 2.01472 \rightarrow 10.01617 + 1.00898 + Q \\ 11.02982 \rightarrow 11.02515 + Q \end{gathered} \quad (6)$$

The masses are measured in *amu* (atomic mass units), one unit of which is equal to one sixteenth the mass of one atom of oxygen ($_8O^{16}$). The sum of the masses of nuclei on the left side of the equation is greater than that on the right side by the energy balance of 0.00467 amu. Using Einstein's mass-energy equivalence expression ($E = mc^2$), it can be shown that one amu is equal to 932 mev, where mev stands for a million electron volts, a very small unit of energy equal to 4.44×10^{-20} kilowatthours. From this relationship, the energy balance can be expressed as:

$$Q = 0.00467 \text{ amu} \times \frac{932 \text{ mev}}{1 \text{ amu}} = 4.35 \text{ mev}$$

The Fission Reaction

Uranium is the heaviest atom occurring in nature. The nucleus of uranium contains 92 protons and is surrounded by 92 orbital electrons. One kind (i.e., isotope) of uranium nucleus, U^{235}, contains 143 neutrons in addition to the 92 protons, giving it an atomic weight of 235. Another and predominating isotope, U^{238}, contains 146 neutrons, raising the atomic weight to 238. When a neutron strikes a U^{235} nucleus in the right way, the nucleus breaks into two nearly equal fragments with great release of energy. Great as this energy is, it is no more, weight for weight, than many other nuclear reactions such as the (d,n) reaction (equation 6) that forms boron from beryllium. Actually, experimental measurements show that about 200 mev of energy is released. This is equivalent to 3.2×10^{-11} watt-seconds. To release a kilowatthour of energy requires the fissioning of 1.12×10^{17} atoms. Even though a hundred million billion atoms seem like quite a few, they weigh only 0.000044 gram (0.0000001 pound) and would be a speck of matter only six-thousandths inch in diameter. To generate the same kilowatthour of energy (at 100-percent efficiency) requires about one-fourth pound of coal. Thus nuclear energy is basically 0.25/0.0000001 or 2.5 million times more effective on a weight basis. Therein lies the importance of nuclear energy. Although there are many more tons of coal than uranium available in the earth's crust, one

two-and-one-half millionth as many tons of uranium would do the same work. Of importance also is the saving in storage capacity and fueling time in the use of uranium as a fuel.

The Conversion of Matter into Energy

In all the reactions mentioned, whether nuclear or chemical, only a fraction of the matter present is transformed into available energy. In the case of the nuclear fusion of hydrogen into helium (as in the hydrogen bomb) this is nearly one percent, some ten times as good as in nuclear fission, but the conversion is still not complete. The sun does just this by converting hydrogen nuclei into helium nuclei, probably as follows:

$$ {}_6C^{12} + {}_1H^1 \rightarrow {}_6C^{13} + {}_{+1}e^0 \quad (7) $$
$$ {}_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14} \quad (8) $$
$$ {}_7N^{14} + {}_1H^1 \rightarrow {}_7N^{15} + {}_{+1}e^0 \quad (9) $$
$$ {}_7N^{15} + {}_1H^1 \rightarrow {}_6C^{12} + {}_2He^4 \quad (10) $$

Notice that although carbon enters into the reaction it is not destroyed; it acts somewhat as a catalyst. The net result of the multi-step reaction is that four hydrogen nuclei have been merged into one of helium. (In the process, two of the protons are converted into neutrons.) In fact, both in this fusion reaction and in the fission of uranium and plutonium the total number of protons and neutrons is not altered. The number of material particles is not changed; they are simply rearranged into a more stable form. The bonus derived as heat energy is related to the difference in stability between the original and the end substances. Or looking at the problem in a different way, the mass of the final substances is slightly less than that of the original substances, the difference being changed into another form of energy.

In the first and third of the hydrogen-to-helium nuclear solar reactions, an electron having a positive charge, ${}_{+1}e^0$, is produced. These positive electrons, usually called positrons, have the same mass as an ordinary negative electron but exist only briefly. Upon collision with a negative electron they combine with it and produce x-rays, which are electromagnetic or light waves having an extremely short wavelength. In this process, two material particles—a positron and an electron—combine to produce radiant energy. Their mass disappears entirely. Thus, in truth, the conversion of ponderable matter to energy is complete.

The reverse process, i.e., matter created from energy, has also been observed. In fact, positrons were first discovered in this way. The hardest (i.e., shortest wavelength) x-rays produced in an x-ray tube operating at more than one million volts produce positron-electron pairs when they pass close to nuclei. The excess energy above the threshold value is converted into the kinetic energy of motion of the pair. The positrons thus formed are, as pointed out, short-lived. They recombine with electrons, the mass of both disappearing in favor of radiant energy, this time of longer wavelength than that which initiated the process. The process, in short, involves a change in frequency of electromagnetic energy.

It is not too much to expect that other and much larger material particles—such as negative protons—can be generated and annihilated in a similar fashion and that these processes will be observed soon. The fundamental building blocks of ordinary matter, protons and neutrons, cannot be created from energy until acceleration energies of the order of ten billion electron volts are available for the conversion. Thus, before x-rays could be used to generate neutrons or protons, it would be necessary to obtain x-rays of the hardness that would be produced in a particle accelerator that operates at about ten billion volts. While this seems large, it is only twice the highest voltages attained so far. The 3-billion-electron-volt (bev) cosmotron at the Brookhaven National Laboratory and the 6-bev bevatron at the University of California are both now in operation. Some cosmic rays have much more than this amount of energy available for inducing reactions. Possibly the first generation of protons and neutrons will be observed by studying the reactions induced by cosmic rays.

Energy from Fission

The natural 92 elements, arranged in the periodic table, extend from the lightest material, hydrogen, to the heaviest, uranium. Each atom of any element consists of a nucleus surrounded by electrons. The nucleus is composed of protons and neutrons, probably cemented together by a mysterious particle called a meson. The lighter elements, such as hydrogen and lithium, are bound together less tightly than those in the middle of the periodic table, such as iron and nickel. Similarly, the nuclei of heavy elements like uranium and thorium are also less tightly bound and are consequently less stable than iron and nickel. In terms of mass, this bears out the fact that when a heavy element such as uranium splits, the weight of the two pieces is less than that of the original atom; similarly, if two very light nuclei are assembled to form a nucleus of intermediate mass, the weight of the resultant nucleus is less than that of the two original nuclei.

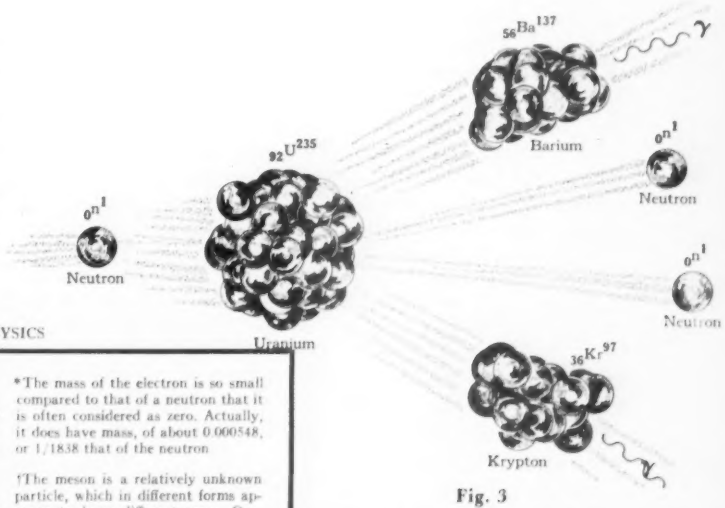


Fig. 3

When a neutron causes fission of uranium 235, a typical reaction produces barium, krypton, two neutrons, plus an energy release due to loss of mass.

TABLE I—BASIC ELEMENTS OF NUCLEAR PHYSICS

Name	*Symbol*	*Mass (approx.)*	*Charge*
Electron	$-_1e^0$	0*	−1
Neutron	$_0n^1$	1.0	0
Proton (also hydrogen nucleus)	p or $_1H^1$	1.0	+1
Deuteron (heavy hydrogen nucleus=2n+2p	D or $_1H^2$	2.0	+1
Positron	$_{+1}e^0$	0	+1
Alpha particle (helium nucleus)	α or $_2He^4$	4	+2
Gamma ray	γ	0	0
Meson		0–0.3†	+1 or 0

*The mass of the electron is so small compared to that of a neutron that it is often considered as zero. Actually, it does have mass, of about 0.000548, or 1/1838 that of the neutron.

†The meson is a relatively unknown particle, which in different forms appears to have different mass. One, called the pi meson, has a mass approximately 300 times that of the electron; another, called the mu meson has a mass about 200 times that of the electron.

The difference in each case appears as energy.

This energy is enormous, even though in the process of fission of uranium only one part in 1000 (1/10 percent) of the mass is transformed into energy. In the fusion of atomic nuclei or in the fission of uranium, the possibility exists of obtaining enormous amounts of energy. This possibility is difficult to realize in practice. Energy by way of fission is possible only because of certain unusual properties of uranium.

When a uranium atom separates into two fragments through fission (Fig. 3), the two parts rush apart with enormous speed (which means they have high energy), since they bear charges of the same sign due to the positively charged protons in the nuclei. A typical fission reaction is:

$$_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{56}Ba^{137} + {}_{36}Kr^{97} + 2{}_{0}n^{1} + Q \qquad (11)$$

The energy release Q can be calculated from the difference in masses of the various nuclei on the two sides of the equation. Thus, the masses of $_{92}U^{235}$ and the projectile neutron $_{0}n^{1}$ are 235.1156 and 1.0090, respectively, for a total of 236.1246 amu. The masses of the products, barium ($_{56}Ba^{137}$), krypton ($_{36}Kr^{97}$), and two neutrons are 136.9514, 96.9520, and 2.0180 amu, respectively, for a total of 235.9214 amu. The difference in mass before and after fission is 0.2032 amu less, or, in energy, 190 mev. Actually, such calculations are not very accurate and the true value may be somewhat different. Other fission reactions are also possible, giving fission products ranging from zinc to gadolinium, covering a span of 35 elements and 200 isotopes.

The energy available from the fission process manifests itself through electrical charges pushing the two fragments apart, and is equal to the available mass energy (190 mev) just calculated. Since the charge of the barium fragment is 56 and the krypton fragment 36, only the distance separating them is needed to calculate the energy available. The radius R of nuclei is given approximately by the empirical equation:

$$R = (1.5\times10^{-13})\ A^{1/3}\ \text{cm} \qquad (12)$$

where A is the mass number (total number of protons and neutrons). So, for the two fission fragments, the radii are:

$$R_{Kr} = 1.5\times10^{-13}\times97^{1/3}\ \text{cm} = 6.9\times10^{-13}\ \text{cm} \qquad (13)$$

$$R_{Ba} = 1.5\times10^{-13}\times137^{1/3}\ \text{cm} = 7.7\times10^{-13}\ \text{cm} \qquad (14)$$

At the instant of fission the new-born nuclei are separated by the sum of the two radii, which is 14.6×10^{-13} cm. The electrical energy for pushing the two nuclei apart can be obtained from a Coulomb equation:

$$E = \frac{q_1 q_2}{r} \qquad (15)$$

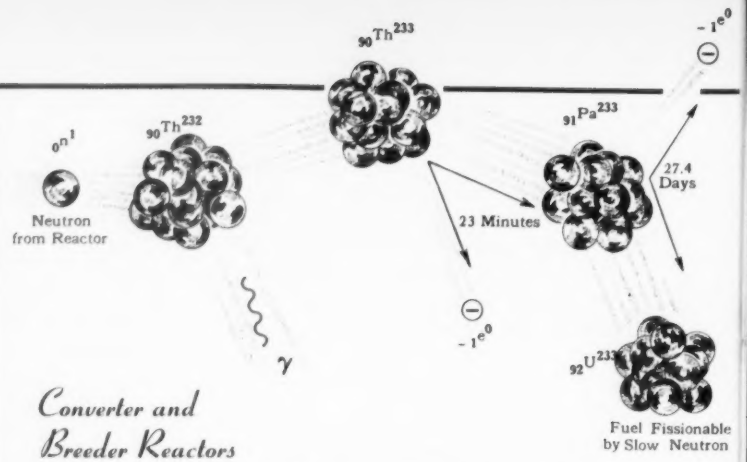
where q_1 and q_2 are the charges of the two nuclei and r is their separation. It follows that:

$$E = \frac{36(4.8\times10^{-10})\times56(4.8\times10^{-10})}{14.6\times10^{-13}} = 320\times10^{-6}\ \text{ergs} \qquad (16)$$

where 36 and 56 are the number of protons in the krypton and barium nuclei, respectively. The factor 4.8×10^{-10} is used to convert the charge of the proton to electrostatic units. This energy can be expressed as:

$$E = 320\times10^{-6}\ \text{ergs} \times \frac{1\ \text{mev}}{1.6\times10^{-6}\ \text{ergs}} = 200\ \text{mev} \qquad (17)$$

The values of the nuclear radii calculated above are not particularly accurate, but the value for E obtained from the Coulomb calculation is in satisfactory agreement with the calculation from mass considerations of equation (11). Thus the mass energy released in fission is manifested through the electrical repulsion of the fission fragments and appears as kinetic energy of these particles, which becomes heat energy as the fission products tear their way through the surrounding material and are slowed down.



Converter and Breeder Reactors

The neutrons in a reactor can be used to manufacture, from fertile materials, certain other nuclei that fission with slow neutrons. These artificially produced fuels can either be removed from the reactor and used as fuel for other reactors, or "burned" in place as a way of augmenting the lifetime of the reactor. The fission process emits about 2.5 neutrons on the average; one is required to cause fission in order to perpetuate the chain reaction, leaving only 1.5 neutrons to generate new materials and to take care of the losses of neutrons due to leakage and capture. If a reactor is required to make as much fissionable material as it consumes, one of the remaining 1.5 neutrons must always be used to generate new fuel, leaving only 0.5 neutron for leakage and capture by

Fission Chain Reaction

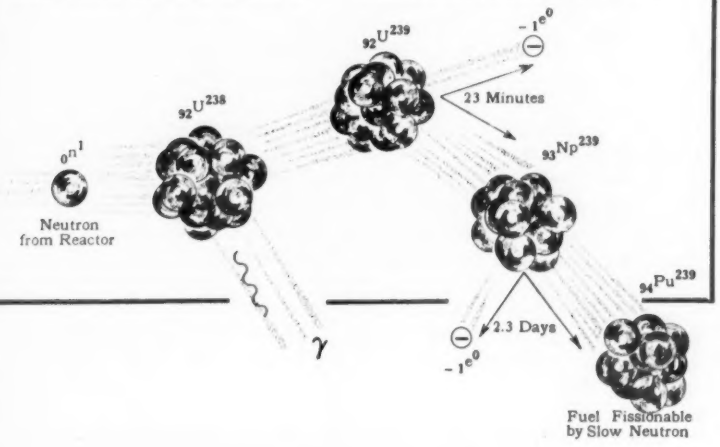
The essential thing about uranium fission that makes a chain reaction possible is that the uranium atoms split in such a way as to liberate several free neutrons, about 2½ on the average. This neutron liberation makes a self-maintaining process possible. The splitting requires a neutron to make it "go," and the splitting process itself acts as a source of neutrons that can cause more uranium atoms to split. Here is the basis of a self-maintaining process, technically known as a chain reaction. This can be compared to ordinary combustion, which is a type of chain reaction wherein temperature plays the same part as the neutrons do in a reactor.

Why then does not ordinary uranium explode or at least "burn nuclearly"? There are complications. Theoretically, because several neutrons are released in every fission, a chain reaction is possible. The determining factor is what happens to those product neutrons. One of the 2½ neutrons released must actually produce another fission to keep the process going. Otherwise the nuclear "fire" goes out.

If all the neutrons released produced more fissions immediately, the material would explode violently. But because neutrons move rather freely through matter (like x-rays) many are lost by escaping through the surface of the lump of uranium. Remedy: use a big enough lump to get a sufficiently small surface-to-volume ratio. In other words, unless the

nonfission processes. The breeder reactor therefore places a great premium on neutron economy. Emphasis must be placed on (1) keeping as many of the generated neutrons as possible within the reactor and (2) reducing the loss of neutrons to the reactor structural materials and to nonfission capture. Item (1) is assisted by careful reactor design and (2) by selection of materials of low neutron cross section and by elevating the neutron energy to higher values where the cross section is greatly reduced for their capture by nonfission processes.

When a reactor produces more than one new fissionable nucleus for each one destroyed, it is said to be a *breeder*. If the fuel produced is not greater than that used and the reactor uses the generated fuel to augment its lifetime, the reactor is called a *converter*. The nuclear processes of fuel generation may be the same for the breeder and for the converter. Two fuel-producing reactions are shown below and at left.



lump of fissionable material exceeds a certain critical size the chain reaction cannot proceed.

Another complication is that impurities in the uranium are powerful absorbers of neutrons. They steal away some of the neutrons essential to continuation of the process. This is difficult to remedy, because appreciable losses or "poisoning" result from the presence of only one part per million of certain impurities, and it is no easy matter to manufacture anything of the required purity on an industrial scale.

The most serious complication of all is that uranium itself absorbs neutrons in other ways than those that result in fission. This phenomenon was both a blessing and a curse to the aims of the military project. It turns out that the overall effect of this nonfission absorption of neutrons by uranium is sufficiently great to prevent a chain reaction in perfectly pure natural uranium, even in so large a lump that escape of neutrons through the surface is negligible.

Neutrons given out in fission are "fast," i.e., have speeds of about 10 000 miles per second, corresponding to several million electron volts of kinetic energy. Such fast neutrons colliding with uranium atoms have a rather great chance of losing some of their energy without either being caught or producing fission.

Neutrons of intermediate speed produced this way are unable to produce fission in U^{238}. They can do so only in U^{235}, which forms only 1/140th part of natural uranium. Neutrons of a particular low energy (about ten electron volts) are very likely to be captured by U^{238} to form U^{239}. This is very important in reactor design. More on this later. This happens readily, and so many neutrons are used up this way that a chain reaction cannot be maintained in pure ordinary uranium regardless of the size of the sample.

An uncaptured neutron continually loses energy by colliding with atoms as it diffuses throughout any material, until its average energy is that of the thermal motion of the atoms of the material. It is these thermal neutrons of certain extremely low energies, i.e., less than an electron volt, which are strongly captured by U^{235} to produce fission.

The clue to *possibly* making the chain reaction go with ordinary metallic uranium, which contains all kinds of uranium atoms but is predominantly U^{238}, lies in arranging the uranium in a lattice of small lumps so that many of the fast-moving neutrons diffuse out of the uranium into some surrounding material. Here many of them would be slowed down to well below ten electron volts before diffusing back into the uranium. By this means a higher proportion of neutrons is preserved for the fission of U^{235} by making them less likely to be caught by U^{238}.

In the technical vocabulary of nuclear engineering, this other material, which keeps neutrons in custody and helps them lose energy until they are safe from capture by U^{238}, is called the "moderator." Evidently the moderator material also must not absorb too many neutrons or the reaction would be stopped. The moderator, in addition to not absorbing neutrons, should have a low atomic weight. This is because the neutrons to be slowed collide elastically with the nuclei of the moderator material, and give up more energy at each impact if the two partners of the collision have nearly the same mass. The hydrogen in water, being the element with least mass, would, from a weight standpoint, be the best moderator. However, unfortunately, the single proton that comprises the hydrogen nucleus has a great tendency to absorb a neutron (resulting in the formation of a deuteron and a γ-ray). Heavy water, which contains heavy hydrogen or deuterium, is satisfactory from a neutron-absorption standpoint, but is a scarce and costly substance. Helium, next in the scale of elements, would be suitable except that it is a gas at all but impractically low temperature, and is therefore not dense enough to provide adequate slowing-down targets for neutrons. Metallic beryllium is a good possibility, but has been too expensive. Lithium and boron are strong neutron absorbers and hence are unsuitable as moderators. High-purity carbon, in the form of graphite, is more readily available and is a low-cost material with acceptable absorption properties, and has been used as the moderator in many chain-reacting piles or nuclear reactors, including the famous "first" at the University of Chicago. However, graphite has poor structural strength in that it has a very low breaking stress; and, further, a carbon moderator requires four times as many collisions to slow down fission neutrons to thermal speeds as does a heavy water moderator.

Controlling the Nuclear Reactor

If the reactor is so constructed that, on the average, more than one fission results from the neutrons produced by each fission, then clearly the number of neutrons present, and the heat generated, increases by the compound-interest law. If a great multiplication happens rapidly, say, in a small fraction of a second, then the phenomenon becomes an explosion. In short, this is a sort of atomic bomb. Even if the reaction occurs slowly, the reactor would be destroyed by melting if the multiplication were allowed to proceed indefinitely.

One way to control the reactor is to provide passageways through it, into which rods of material that strongly absorb neutrons can be placed. When these rods are fully inserted into the mass of fissioning material, they absorb so many neutrons that the chain reaction is stopped. As they are slowly withdrawn, a point is reached at which the reaction is just able to maintain itself; if the rods are pulled out farther the neutrons are able to multiply and the reactor operates at increasing power levels. To reduce the multiplication rate, the absorbing rods are simply pushed back in. Thus to raise the reactor power output, control rods are withdrawn to multiply the number of neutrons, then returned to the operating point; the reactor then operates at a higher power level. The procedure is reversed to lower the power level. Cadmium, boron-containing steel, and several other materials are suitable for the control rods.

The language of the preceding paragraph implies that the time scale is slow enough for an operator to maintain control by manual operation of control rods, or by use of a similar relatively slow-acting control mechanism. That is in fact the case, owing to another phenomenon in the fundamental physics of fission: *delayed* neutrons.

Most, but not all, neutrons emitted in the fission process come out instantly. The uranium nucleus in splitting apart spills out about 99 percent of the neutrons immediately. These are called *prompt* neutrons. The atomic fragments are also in a highly unstable condition and some of them throw out additional neutrons after a short time delay, amounting, on the average, to about 10 seconds. These delayed neutrons set the time scale on which the neutron multiplication in the reactor builds up, and set it for such a long time that slow-acting controls are easily able to regulate the activity of the pile.

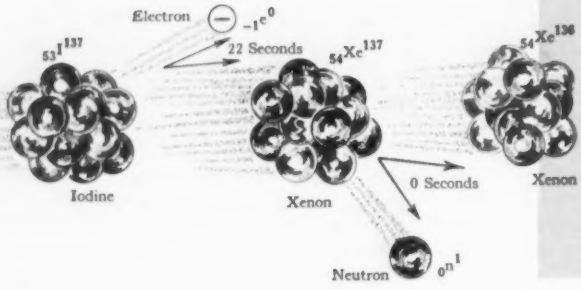
not occur and the chain reaction is made possible. In the bomb, the main factors tending to prevent criticality are the escape of neutrons through the surface and the losses of neutrons by nonfission absorption due to impurities, including any remaining U^{238}.

Plutonium is a newly discovered chemical element not known to exist in nature, but which is made from uranium by nuclear transmutation. Plutonium is important because it, like U^{235}, is fissionable by slow and intermediate neutrons.

Plutonium is a man-made material, produced from U^{238}. When U^{238} captures a neutron it becomes U^{239} with the simultaneous emission of gamma radiation. This U^{239} is not stable, but emits high-speed electrons by a process of spontaneous radioactivity. The mean life of the U^{239} atoms is only about 30 minutes. By this activity they are transformed into atoms having essentially the same mass but one greater positive charge, 93, on the nucleus. Thus is formed a new chemical element called neptunium, and written Np^{239}. Neptunium-239 is also spontaneously radioactive and emits another high-speed electron, becoming thereby an atom having 94 positive charges on the nucleus, but still essentially of mass 239 (because the mass of an electron or positron is so small compared to that of a neutron or proton that the addition or loss of one from a heavy nucleus is inconsequential). This process is slower; the mean life of the neptunium atoms is about three days. The resulting atom of charge 94 and mass 239 is another new element called plutonium, and written Pu^{239}.

The purpose of reactors at Hanford, Washington is not to get atomic power but to produce the new element plutonium, which provides a second bomb material. It is, in short, a competitor of U^{235}. Plutonium is sought as a bomb material, not so much because it is superior to U^{235}, but because it is a chemically different element and its separation from uranium is vastly easier than the separation of the various isotopes of uranium. Further, the production of plutonium makes use of U^{238}, which is relatively plentiful and otherwise of little value. The process by which plutonium is formed—capture of neutrons by U^{238}—has already been mentioned as one that tends to stop the chain reaction in a pile. Nevertheless, the uranium lumps in the pile are exposed to a dense atmosphere of neutrons, and so the means is at hand for changing a part of the U^{238} into Pu^{239}.

Delayed Neutrons



The neutrons resulting directly from fission are called *prompt* neutrons; they do not have a single energy, but are emitted with a spectrum of energies, which has a maximum near 1 mev. The average prompt neutron energy is about 2 mev.

In addition to the prompt neutrons released at fission, the fission fragments decay along various radioactive chains, and some of the members of these chains themselves give off *delayed neutrons*. The time at which these are emitted subsequent to fission is determined by the radioactive decay periods of the precursors of the delayed-neutron emitting nuclei. Thus, for example, one of the delayed neutron emitters, having a delay of 32 seconds, is known to be Xe^{137}, which is a member of the fission fragment chain:

$$_{53}I^{137} \xrightarrow[22\ \text{sec}]{-1e^0} {}_{54}Xe^{137} \xrightarrow[0\ \text{sec}]{0n^1} {}_{54}Xe^{136}\ \text{(stable)}$$

The Bomb Chain Reaction

The chain reaction in an atomic bomb proceeds explosively, whereas the process in the reactor can be easily controlled by manual operation of neutron-absorbing rods. The key distinction is that the bomb (one type) is made of essentially pure U^{235}, without moderator. The chain reaction in the bomb is carried on principally by fast neutrons (i.e., those having energies above 1000 electron volts) directly released by fission. As already remarked, a chain reaction cannot be maintained in pure natural uranium because of the nonfission absorption in U^{238} of neutrons having energies of less than 1 mev. With essentially pure U^{235} these competing absorption processes do

Breeding

In the production of plutonium, U^{235} is fissioned to produce heat and additional neutrons, one of which is needed to continue the reaction, but some of which are used to convert the otherwise useless and predominant U^{238} into plutonium, which is fissionable. Thus, this situation exists: in the fission process, heat is developed, which in a reactor suitably designed could be put to profitable use, and, in addition, more fissionable material is produced. This offers the intriguing possibility that if the process could be made sufficiently efficient, more fissionable material would be produced than is consumed. This is known as breeding. Conceivably it might be possible to convert all the U^{238} to fissionable material, i.e., plutonium, and thereby increase the total stock of fissionable material by the ratio in which U^{238} predominates in nature over U^{235}, or about 140 times. Also by a similar breeding process, it is theoretically possible to convert thorium-232, a nonfissioning material (in the sense that it will not sustain a chain reaction), into U^{233}, which, like U^{235}, is capable of slow-neutron fission.

Unfortunately, however, breeding isn't quite as simple as it seems at first glance. One of the stumbling blocks is the need for complicated and expensive chemical processing to remove and purify the fissionable materials made in the breeder. Further, two fission product atoms are made by each fission reaction; some of these atoms are "poisonous" to the reactor, i.e., they are big absorbers of neutrons. After the reactor has been in operation for a time, the poisons must be removed so that the reactor can continue to operate, or the reactor must be specially designed to take care of this contingency.

Five important delayed neutron groups and the fraction that each constitutes of all neutrons, both prompt and delayed, are tabulated below for U^{235}.

τ_i (half-life, sec)	β_i (relative abundance)
55.6	2.6×10^{-4}
22.0	17.0×10^{-4}
4.51	21.0×10^{-4}
1.52	24.0×10^{-4}
0.43	8.4×10^{-4}
	$\Sigma=73.0\times10^{-4}$

Evidently, about 0.7 percent of all the neutrons produced from fission are delayed. These neutrons, delayed about ten seconds on the average, also have an energy spectrum, the average neutron energy being about 0.5 mev as compared to the prompt neutron average energy of approximately 2 mev.

Another stumbling block is the "radiation damage" inflicted on the fuel elements and reactor structural materials by the intense radiation in the reactor. Radiation damage is the term applied to changes in the properties of materials due to irradiation by neutrons, γ-rays, and other nuclear particles. It may be evidenced by warping, hardening, and other changes in reactor materials. Radiation damage may very well be the factor that determines the degree to which regeneration can be allowed to take place.

However important the cost of chemical processing and the effects of radiation damage may be, the "64-dollar question" is whether the desired regeneration rate can be obtained. The Experimental Breeder Reactor (EBR), the first reactor designed to answer this question, has been placed in operation at the National Reactor Testing Station in Idaho by the Argonne National Laboratory. Subsequently, the Atomic Energy Commission announced that the EBR is able to generate as much fuel as it consumes and that the breeding principle has been successfully demonstrated.

Atomic Energy versus Atomic Power

Although the invention and use of dynamite did demonstrate certain aspects of the utility of molecular energy, it did not lead directly to the internal combustion engine. Similarly, the existence of nuclear fission and atomic bombs does not guarantee or necessarily imply the possibility of useful atomic power. In the fission process, the resulting fragments are given off with tremendous energies of about 100 million electron volts each and are highly charged electrically. It is natural to wonder if it would be possible to use these projectiles to generate electrical power directly by allowing them to move through electromagnetic fields. Unfortunately, means have not yet been developed to do this as efficiently as the molecular temperature of the burning gases is used in the internal combustion engine. In present nuclear reactors, the fuel-bearing materials are used as transducers to reduce the high-energy particles to thermal energies through collisions of the fission fragments with the surrounding molecules in the fuel and structural materials of the reactor. By these collisions the struck atoms are heated and the various surfaces near the fuel within the reactor are heated.

Details of the Operation of a Reactor

Reactors utilize for their fuel any of the fissionable nuclei that can sustain a chain reaction and be obtained in sufficient quantity to originate the chain. In present-day reactors most of the fissions are produced in U^{235} or Pu^{239}. The fission of one of these nuclei releases about 195 mev of energy—165 mev in the form of kinetic energy of the fission particles and 30 mev that is associated with neutron and β- and γ-ray energy. The fission fragments penetrate about 0.000 5 inch into the surrounding reactor materials. Thus in most reactors the fission energy is transformed into heat inside the reactor fuel elements within a very short distance from the point of fission. To establish a thermal energy of 100 000 kilowatts, the reactor must produce 3×10^{18} fissions per second. The chain reaction within the reactor must be kept just at criticality, that is, the production rate of neutrons must be precisely the same as the rate of loss of neutrons by leakage from the reactor plus the rate of absorption of neutrons within the reactor. The equation for the balance of neutrons for the reactor assembly is then:

$$\text{Leakage}+\text{Absorption}=\text{Production} \qquad (18)$$

A practical power reactor operates most of the time at a steady power level and, since this level is proportional to the rate of production of fissions, the power production is proportional to the rate at which neutrons are produced. The size and shape of the reactor, the nuclear characteristics of materials comprising the reactor, as well as other effects, all influence the ability to maintain the chain reaction. The factors that determine the criticality are more precisely:

1—*Geometry*. This includes the external size and shape of the reactor and the detailed arrangement of the fissionable and other materials within the reactor. Small, high-power reactors, such as the Submarine Thermal Reactor (STR), which will propel the submarine U.S.S. *Nautilus*, have stringent geometry requirements.

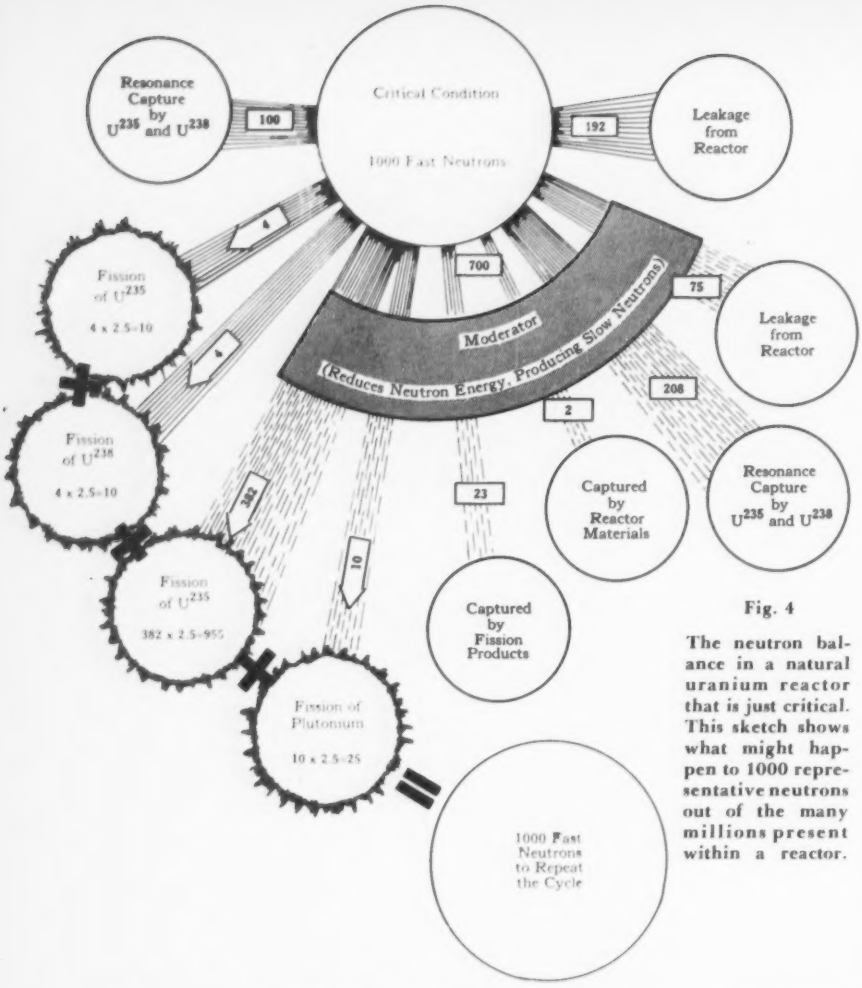


Fig. 4

The neutron balance in a natural uranium reactor that is just critical. This sketch shows what might happen to 1000 representative neutrons out of the many millions present within a reactor.

2—Migration Length. Neutrons are born in the nuclear fission process and move about until they either escape from the reactor or are absorbed by the materials of the reactor. In the course of its journey, the neutron makes many collisions with materials within the reactor. The net distance traveled by the neutron from its birth in fission to its eventual loss or capture is called the migration length. It sets the geometrical scale for the size of the reactor and depends mainly on the nuclear properties of the materials of the reactor.

3—The Multiplication Constant. To maintain the chain reaction, the number of neutrons produced within the reactor must be equal to the number lost or absorbed, as stated by equation (18). The multiplication constant k is the ratio of the total number of neutrons produced during a small fraction of a second to the total number of neutrons lost or absorbed during that same time. The chief problem in reactor control is to keep this ratio exactly equal to one. The value of k is then the ratio of the number of neutrons present in two successive neutron generations. Since one neutron is required to produce a fission, the neutrons in each generation increase by a factor of $(k\text{-}1)$. If n neutrons were present at a particular time, then $n(k\text{-}1)$ will be present one generation later. The rate of change in the number of neutrons is:

$$\frac{dn}{dt}=\frac{n(k\text{-}1)}{l} \tag{19}$$

where l is the average time required for the formation of a new generation of neutrons. Upon integration, the number of neutrons present after a time t is:

$$n=n_0\, e^{(k\text{-}1)\,t/l} \tag{20}$$

where n_0 is the initial number of neutrons at time $t=0$. It is clear that, unless suitably controlled, the number of neutrons in a nuclear reactor, and consequently the reactor power, increases exponentially with time, provided k is greater than unity, i.e., the reactor is supercritical. Suppose a reactor has been barely brought to supercriticality with $k=1.002$, and is operating at a low power of one watt. Assume that the average neutron lifetime l is 0.0001 second. If conditions remained unchanged the reactor power would rise to 100 megawatts in a time:

$$t=\frac{l}{k\text{-}1}\,ln\left[\frac{n}{n_0}\right]=\frac{0.0001}{0.002}\,ln10^8=\text{approx. 1 sec} \tag{21}$$

where the ratio of numbers of neutrons is equal to the ratio of power levels. If 100 megawatts were the desired power level, control means to reduce k to unity would be required when the neutron flux reached such a level that 100 megawatts of fission energy were being produced. This control is usually accomplished by moving neutron-absorbing rods into the reactor to collect some of the neutrons, thereby reducing the value of k. Obviously the rods must be moved fairly rapidly to prevent the reactor from melting. Just how rapidly will be considered in more detail later in this article.

Neutron Balance

Except for a few neutrons from an artificial source used to start the reactor, all of the neutrons present are produced in the fission process. Not all of these neutrons so produced cause fission of other uranium nuclei. Many nuclear processes occur that influence the ability of the reactor to maintain criticality. These are:

1—Leakage of neutrons from the reactor before they are slowed down.

2—Leakage of neutrons after they become slow.

3—Fission of U^{235} by slow neutrons.

4—Fission of U^{235} by fast neutrons.

5—Fission of U^{238} by fast neutrons.

6—Nonfission capture of neutrons by U^{235} forming U^{236}, or by U^{238} forming U^{239}, the latter decaying first into neptunium and then into plutonium. These capture events are most likely to occur for particular values of the neutron energy called "resonance energies." This is sometimes called "resonance capture."

7—Capture of neutrons by structural, control-rod, or moderator materials in the reactor.

8—Capture of neutrons by the products of previous fissions or capture processes. This and the previous effect constitute "parasitic capture."

9—Neutron-induced fission of the products of previous capture reactions such as plutonium, which is produced by a process sometimes called "conversion."

The importance of the various processes to the maintenance of a chain reaction varies greatly with the particular reactor design. To get some idea of how the neutrons are used and lost within the reactor, the magnitude of the preceding effects must be evaluated.

The neutron balance that exists in a critical reactor can be illustrated by watching what happens to 1000 representative neutrons of the many millions that are present within the reactor (see Fig. 4).

Types of Reactors

Most contemplated power nuclear reactors use highly enriched, slightly enriched, or natural uranium. The relative importance of the various events that influence the life of a neutron is quite different for each type. Naturally, a detailed analysis of each reactor is required before it can be mechanically designed.

Reactors can also be distinguished by the neutron energy at which most of the fissioning takes place. The Submarine Thermal Reactor is called a "thermal reactor" because most of the neutrons are moderated so that they are nearly in thermal equilibrium with the water in the reactor. This means that most of the neutrons have energies of about 0.03 electron volt. The reactors at Hanford and the original "pile" at the University of Chicago are other examples of thermal reactors.

Reactors in which most of the fissions are caused by neutrons having energies above the thermal range but not over about 1000 ev are called "intermediate reactors," since they use neutrons in the intermediate energy range. A typical example of this type reactor is the Submarine Intermediate Reactor (SIR), being developed by the General Electric Company for application in another atomic-powered submarine, U.S.S. *Sea Wolf*.

If a reactor has most of the fissions originated by neutrons with energies above 1000 ev, it is called a "fast reactor," since it uses very high speed neutrons. An example of a transient fast reactor is the atomic bomb. However, stable operation of a fast reactor is possible and such a device has been operated at the Los Alamos Scientific Laboratory.

Multiplication of Neutrons in Thermal Reactors

Thermal reactors such as the STR are generally simpler theoretically than other types and the nuclear constants for them are better understood. Since the probability of fission is highest for low-energy neutrons, a thermal reactor of a given size can be made critical with smaller amounts of fissionable material than are required for the other reactor types. Thus, except for poisoning effects by fission products (whose cross sections are also high for low-energy neutrons), the thermal reactor possesses a definite advantage in the ability to attain criticality with a minimum of scarce fissionable material.

The average number of neutrons emitted per fission is represented by ν, which is about 2.5 for U^{235}. Not all of the neutrons absorbed by the reactor fuel produce fission, since in certain cases the uranium may collect a neutron without fission. The quantity σ_u, is the cross section for both fission and nonfission absorption of slow neutrons by the fuel (uranium), and σ_f, is the cross section for fission absorption of slow neutrons by the fuel. The cross section for an event is a measure of the probability of its occurrence. The number of fast neutrons generated for each slow neutron absorbed by the fuel are then:

$$\eta = \nu \frac{\sigma_f}{\sigma_u} \qquad (22)$$

where ν is the average number of fast neutrons generated in each fission. Most, but not all, fissions are caused by slow neutrons. Fast neutrons cause some augmentation of the neutron population so a factor ϵ is used to account for this

Glossary of Nuclear Terms

The Atomic Weight of an element is the weight of one of its atoms relative to that of an oxygen atom (16.0000).

The Atomic Number of an element is the number of protons in the nucleus of one of its atoms and, since an atom is neutral, is also the number of its planetary electrons.

The Mass Number of an element is the integer nearest its atomic weight. Since the weight of an atom is determined almost entirely by its protons and neutrons, each of which has a weight close to unity, the mass number is also equal to the total number of nuclear protons and neutrons.

An Electron Volt is the energy acquired by an electron accelerated by an electric field through a potential difference of one volt; it is very minute, being equal to about five trillion-trillionths of a kilowatthour.

Critical is the term used to describe the condition of a nuclear reactor in which a fission chain reaction is being maintained at a constant rate. A reactor in which the rate of fissioning is increasing is said to be supercritical and one in which the rate is decreasing (i.e., there is no chain reaction) is termed subcritical.

The Multiplication Factor is the ratio of the number of neutrons in one neutron generation to the number in the immediately preceding generation. Whether the reactor is subcritical, critical, or supercritical depends upon whether this factor is less than, equal to, or greater than one.

Fissionable Materials are, strictly speaking, not simply those which undergo fission, but rather those which can sustain a fission chain reaction.

Fertile Materials are nonfissionable materials that can be converted in reactors to fissionable materials.

The Moderator is the material that is placed in a reactor for the express purpose of slowing down neutrons away from the fuel in order to avoid resonance capture. It should have low atomic weight and should not appreciably absorb neutrons.

Thermal Neutrons have about the same average kinetic energies as the molecules of the medium in which they are present. These energies, in the neighborhood of 0.03 electron volt, are relatively low and such neutrons are termed slow. Neutrons having energies between thermal and about 1000 electron volts are called intermediate neutrons and those above this range are fast.

A Thermal Reactor is one in which most of the fissions result from the capture of thermal neutrons. In intermediate and fast reactors most of the fissions are due to the absorption of intermediate and fast neutrons, respectively.

A Breeder Reactor is one that produces more fissionable material than it consumes.

A Production Reactor is one that generates fissionable materials from fertile materials, but which consumes at least as much fissionable material as it produces. It is sometimes called a regenerative reactor.

A Converter Reactor is similar to a production reactor, except that it utilizes the fissionable material produced to augment its lifetime.

The Microscopic Cross Section for a nuclear reaction is the ratio of the fraction of target nuclei that react to the number of incident particles per unit area of the target material; it is the effective cross-sectional area presented by a single nucleus for the reaction, but is not necessarily related to the geometrical cross-sectional area of the nucleus. The cross section for a reaction depends upon the particular type of reaction and the energy of the incident particle, but a typical microscopic cross section is of the order of 10^{-24} cm^2 per nucleus, which unit is called a "barn."

A Negative Temperature Coefficient is possessed by a reactor whose multiplication factor decreases slightly with increasing temperature or rises slightly with decreasing temperature. If the temperature of such a reactor rises for some reason, the multiplication factor decreases, causing the reactor temperature to fall. As the temperature falls to its original value, the multiplication factor increases to its original value. A similar stabilizing sequence will take place if the temperature originally decreases.

effect. The fast-fission factor ϵ is defined as the total number of fast neutrons produced by fissions due to neutrons of all energies, divided by the number of fast neutrons due to thermal fissions. Usually ϵ is not a large quantity in thermal reactors and has a value of about 1.03.

On the average, for each slow neutron absorbed in fuel, ϵn fast neutrons are formed in the next generation. These fast neutrons are slowed down by collisions with the atoms of the moderator, which in the STR are the hydrogen atoms in the water. During the slowing down process, some of the neutrons are captured in nonfission processes, mostly at resonance energies, so that only a fraction p of the fast neutrons generated remain after becoming slowed down. The fraction p is termed the "resonance escape probability." The number of slow neutrons in this new generation for each thermal neutron that belonged to the previous generation and was absorbed in fuel is then $p\epsilon n$.

To cause the chain reaction to maintain itself, these new slow neutrons must cause fission; however, not all of them are absorbed by the fuel, since some are lost by absorption in structural and moderator materials and in poisons within the reactor. If a fraction f of these new slow neutrons is absorbed within the fuel, the net number of neutrons absorbed in fuel in this new generation for each neutron so absorbed in the previous generation is:

$$k = f\,\epsilon\,p\,n \tag{23}$$

where f is called the "thermal utilization." The term k is called the "multiplication constant," since it is the ratio of the number of neutrons absorbed in one generation to those absorbed in the preceding generation. To maintain a chain reaction at a steady state, the multiplication constant k must be exactly equal to one.

These reactor conditions have been evaluated for the case in which no neutrons are lost by escape outside of the reactor; the reactor is assumed to be infinitely large. Power reactors such as the STR are small and the leakage of neutrons to the surroundings is not negligible, even though neutron reflectors are provided in an attempt to keep the neutrons within the reactor. For finite size reactors, call Q the probability that a neutron does *not* escape by leakage. The condition for steady-state criticality of a finite reactor is then given by:

$$k\,Q = f\,\epsilon\,p\,n\,Q = 1$$

This is the condition the operator must maintain to produce a constant power within the STR nuclear-power plant. The reactor is said to be subcritical, critical, or supercritical depending on whether kQ is less than, just equal to, or greater than one. Since the power will decrease or rise exponentially if kQ is not equal to unity, complicated control techniques are required for accurately establishing and maintaining criticality of a reactor.

Delayed Neutrons and Reactor Control

The prime source of information for reactor control is the measurement of the intensity of the neutrons that leak out of the reactor. Special neutron-counting devices are used for this purpose. Fortunately, nature assists in control of nuclear reactors. It was shown previously that a reactor would increase in power very rapidly if it became supercritical; so rapid is this increase that it would be very difficult to actuate control systems sufficiently rapidly to maintain criticality. However, not all of the neutrons are emitted immediately in the fission process. At the time of discovery it was difficult to understand how this could be possible; however, it has been found that certain of the radioactive decay products in the fission chain possess excess neutrons to such an extent that they decay by neutron emission. Consider the typical fission reaction in which uranium fissions into bromine and lanthanum:

$$_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{35}Br^{87} + {}_{57}La^{147} + 2{}_{0}n^{1} + \text{Energy} \tag{24}$$

The bromine isotope $_{35}Br^{87}$ decays into krypton $_{36}Kr^{87}$, which is also unstable and decays by two means: (1) normal electron emission to rubidium $_{37}Rb^{87}$ and, (2) the emission of a neutron to the stable krypton isotope $_{36}Kr^{86}$.

Neutrons emitted by such processes are called *delayed* neutrons. Since the half-life (i.e., time for one half of the substance to decay) of $_{35}Br^{87}$ is 55.6 seconds, the neutrons are emitted from its decay product for some time after fission. Even though only a fraction of the neutrons following fission are produced in this manner, they represent a sufficient number to increase the average neutron lifetime from 0.0001 second (the value if all neutrons were emitted promptly at fission) to 0.1 second. This increases the value of l in equation (20) by a factor of 1000, thereby greatly decreasing the rate of multiplication of neutrons. Thus, if neutron-absorbing rods are moved into the reactor within a reasonable number of seconds, reactor transients due to a sudden burst of neutrons can be compensated for and reactor stability maintained.

Power Stability

Water-moderated reactors possess a very desirable stability feature in that they have a relatively high *negative temperature coefficient*.

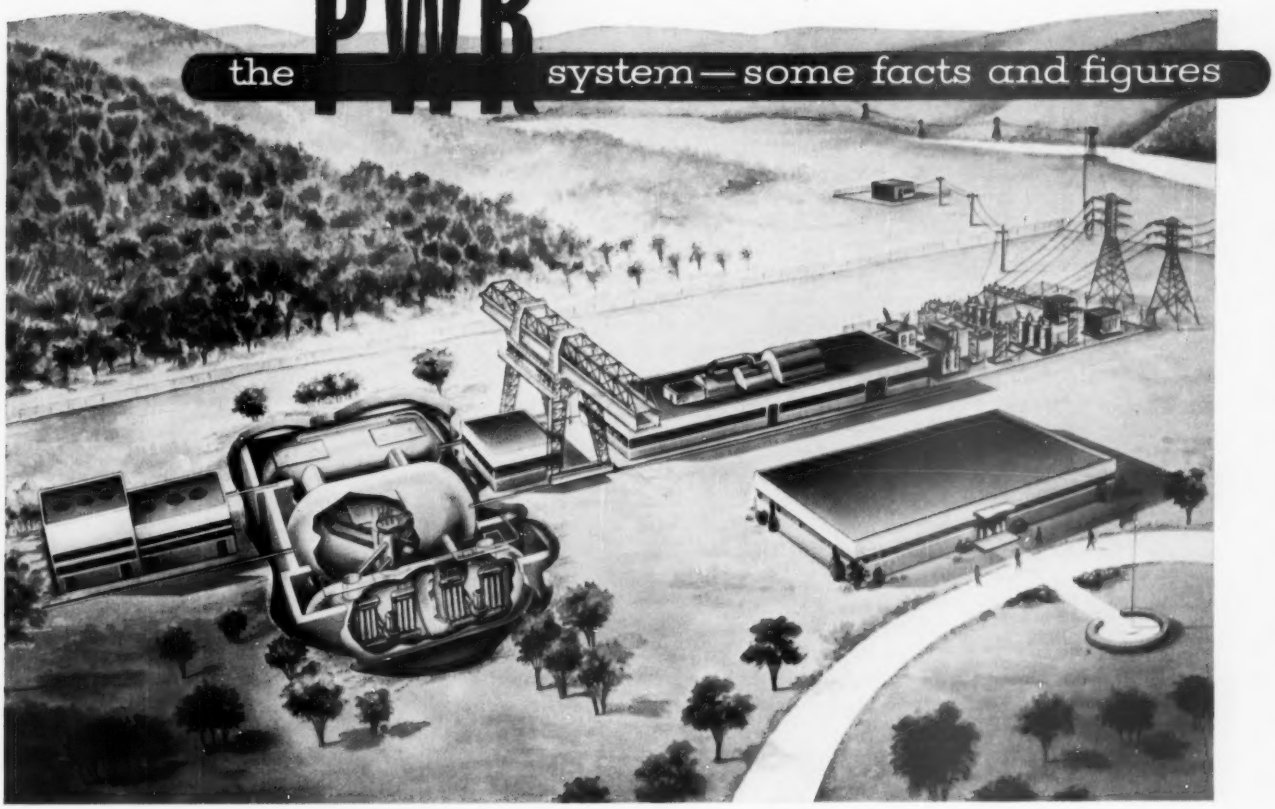
If the temperature of a water-moderated power reactor should rise, due to some unforeseen reason, the reactor tends to operate at lower power, thereby reducing temperature to its original value. Similarly, when the temperature is caused to decrease, the reactor works more effectively and tends to increase the temperature. Hence, *the reactor itself* prefers to operate at a constant temperature. Since the reactor is usually required to operate at constant power, it is generally very desirable that the reactor power plant be inherently able to make corrections for minor perturbations due to temperature fluctuations. The negative temperature coefficient provides an automatic regulation of just this type. This property arises simply from the change in density and thus the moderating ability of the water when the temperature is modified. Some of the water is squeezed out of the reactor core when the temperature is increased and sucked into the core when the temperature is decreased. Since the moderating property of the water is proportional to the amount present within the core, this effect produces a strong stabilizing negative temperature coefficient that is of great value in controlling the reactor and its associated power plant.

The Future

The present existence of a number of different varieties of nuclear reactors—only nine years after the detonation of the first atomic bomb—attests to the speed at which events in this field have transpired. Yet so much unexplored territory remains in nuclear physics and related sciences that future discoveries are certain to exert marked influence on practical application; conceivably the whole approach to practical use could be altered almost overnight by some new bit of information. Just what transpires and how quickly is largely a function of how rapidly new knowledge can be uncovered.

*As far as the atom goes, the Greeks had a word for it—but in this case they were understandably somewhat off base. "Atom" is derived from two Greek words, **a** (not) and **temnein** (to cut), thus meaning something indivisible. 'Tain't so!*

the PWR system—some facts and figures



Work on the nation's first electric-utility nuclear-power plant is now in progress. Herewith some of the characteristics of the plant.

C. H. WEAVER, *Manager, Atomic Power Div., Westinghouse Electric Corporation, Pittsburgh, Pa.*

EFFECTIVE July 1, 1953, Westinghouse was assigned responsibility for the development and design of a pressurized light-water reactor and primary coolant circuit intended as the heat source for generating civilian electric power. To carry out this responsibility, Westinghouse was authorized to do, or cause to be done, the following: (a) such research and development work as is necessary for the design of the reactor and primary coolant circuit; and (b) the necessary design and engineering work, including scheduling of the work and preparation of plans and specifications. Westinghouse was also assigned responsibility for the manufacture, fabrication, assembly, and testing of the pressurized-water reactor.

When Westinghouse commenced work on the primary plant, we were given the following general specifications: (1) generation of at least 60 000 kw of useful electric energy; (2) use of light-water cooled and moderated, slightly enriched uranium-type reactor; (3) 600 pounds per square inch saturated or higher steam conditions; (4) fuel-element life as long as possible between chemical reprocessing; (5) refueling with minimum shutdown period; (6) simplified reactor-control system; (7) central-station-type turbine and electric generating equipment; (8) conventional central-station steam, electric, and other auxiliary systems; (9) commercial standards of equipment; (10) use of concrete for shielding; (11) minimum possible construction cost of the plant; and (12) minimum possible operating cost.

The basic design of the PWR plant is now and for some time has been an established reality. The main coolant system, which serves both to absorb heat generated by the reactor and to deliver heat to the steam generators, will consist of four loops operating off the reactor vessel. Each loop, in turn, consists generally of a pump, a steam generator, shutoff valves, and interconnecting pipe. The pumps continuously circulate coolant water between the reactor and the steam generator. The steam generator, for its part, is the connecting link between the primary system and the steam system. It consists of a water-to-water heat exchanger, and a steam drum and separator. The shutoff valves permit us to isolate one loop if it is not required, or to repair one loop while the other three loops are operating.

The water in the primary plant will circulate at a pressure of some 2000 psi to prevent boiling in the core and to eliminate

(*Above*) **A preliminary sketch of the nation's first central-station atomic power plant. At left are the reactor and heat exchangers. In the center is the turbine-generator, and at right, the switchyard.**

This article consists of extracts from a talk made by C. H. Weaver before the Atomic Industrial Forum in Washington, D.C. on May 24, 1954.

cavitation problems. The average temperature of the primary plant water is maintained at about 525 degrees F.

The primary coolant loops are so designed that the rated plant output is produced with three of the four loops operating. The fourth loop can be operated if desired, but will normally serve as a spare. The loops divide the load equally, and the steam generated by each is fed to a steam header and delivered to the turbine. To produce 60 000 kw net with three loops operating, the pump in each loop circulates water at a rate of about 16 000 gpm. This makes a total of about 48 000 gpm through the reactor. About 1000 hydraulic horsepower is required to circulate the water in each of the three loops.

The primary water is maintained at 2000 psi by a pressurizing tank, which floats on the system and is connected to one of the reactor outlet pipes. This tank is normally filled with about equal volumes of water and saturated steam at more than 6000 degrees F. The head of steam is maintained by electrical heaters in the water. Load changes are accompanied by some volume change of the primary water. The head of steam expands or contracts to accommodate this water-volume change.

The most interesting and highly developmental part of the plant is, of course, the reactor core. It will consist of a geometrical pattern of closely spaced fuel elements. The heat-generating material will be slightly enriched uranium, that is, uranium containing a slightly higher amount of the 235 isotope than natural uranium. More than ten tons of uranium will be used in the first core. The fuel elements will be protected by a corrosion-resistant material designed to prevent the coolant water from becoming contaminated with particles of uranium and fission products.

These fuel elements will be formed into a right circular cylinder about 6 feet in diameter and 7.5 feet high. The maximum fuel-element surface temperature will be less than 636 degrees F, the boiling point of water at 2000 psi. The maximum heat flux will be over 350 000 Btu per square foot per hour, and the average power density will be about 45 kw of heat per liter.

The reactor vessel, which contains the core, will be built large enough to accommodate cores physically bigger than the first one. . . . The vessel shell will be about 9 feet inside diameter and have an overall height of over 25 feet. This shell will consist of carbon steel clad with stainless steel. The cylindrical wall of the vessel will be penetrated by the four inlet and four pipe outlet connections for the four main coolant loops.

The steam generators will consist of two major components: first, the heat exchanger portion, and second, the steam drum. The heat exchanger will consist of a bundle of stainless steel tubes, the ends of which are welded into heavy tube sheets. The entire assembly will be enclosed in a steel shell. Primary coolant will flow through the inside of the tubes. The steam-plant feed water will be fed into the shell side of the heat exchanger and will be converted to steam as it flows upward over the outer surface of the tubes. The steam thus generated will rise to the steam drum where it will be dried by passing through a conventional steam separator. The steam will leave the drum at 600 psia saturated.

Regarding the nuclear control of this plant, we intend taking advantage of the inherent stability of pressurized-water reactors as the basis for control during power changes. Due to the negative temperature coefficient that can be designed into such a reactor, the core will automatically maintain the temperature of water flowing through it at a constant value. Thus, if heat is removed from the primary coolant and

An Engineering Personality

In any given assortment of engineers, backgrounds, experience, and fields of interest are often totally different. So are personalities and philosophies. But in spite of the wide personal differences, one characteristic seems common to all—the deep-rooted urge to improve, to build something better, to find some new approach to an old problem. In John Boyer this tendency manifests itself as a strong curiosity about things technical, and an urgency—amounting almost to impatience—to build better rectifiers and find better ways of using them.

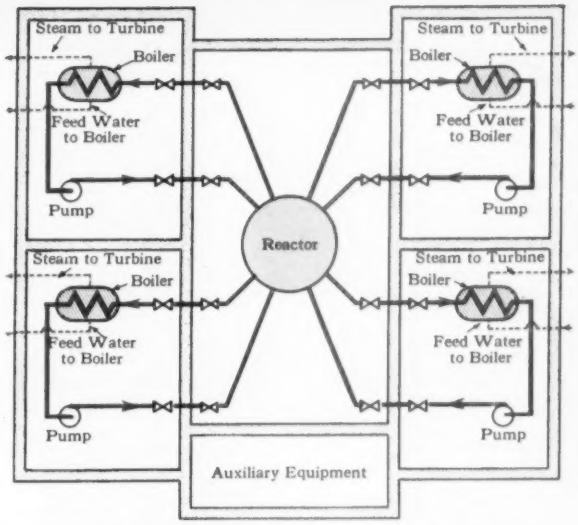
Almost from the day he reported to the rectifier section in 1942, Boyer began asking his associates sharp, persistent, and occasionally embarrassing questions about rectifier technology. As one of his associates puts it, "I think John was surprised, and perhaps even somewhat annoyed, to find that no one knew the answers to some of his questions. Make no mistake, they were good, sound questions; it was just that some of them concerned things that hadn't been tried yet." In the ensuing years Boyer has found most of the answers himself, plus answering a whole flock of others he has thought up in the meantime. Attesting to that fact

if the coolant water temperature therefore decreases, the reactor automatically restores this heat by increasing its power output until the water temperature regains the original value. The reverse is true when the rate at which heat is being removed from the primary water is decreased. The reactor itself accomplishes this control automatically without the operation of any equipment.

The field of power reactors stands today where the infant electrical industry stood some 75 years ago. There was then little doubt that the use of electrical power had a great future, but experts disagreed on whether electricity should be used in the form of direct or alternating current. Those who believed in alternating current could not agree on whether the frequency should be 25, 50, or 60 cycles. The pioneers in those days did not have accurate cost estimates; they could not project their problems accurately into the future; and it was difficult or impossible for them to predict how the many technical problems which faced them would be solved.

In the same way, those of us vitally concerned with nuclear power feel certain that it has an expanding place in the field of energy generation. But we lack the cost and technical data necessary to show that any one type of reactor is greatly superior to all others. We are still far from knowing how to solve all the many cost and technical problems which face each reactor type.

Our experience to date on PWR has confirmed the difficulties of estimating the cost of a new reactor type without actually designing and building it. Recently we obtained, from the nation's most competent vendors, fixed-price sealed bids on the PWR steam generators and also on a prototype main coolant valve. Both bid invitations were based on complete performance specification. The bids received on each component varied by a factor of almost five to one. With such variation in prices for the conventional pieces of equipment, as quoted by qualified manufacturers, it seems clear that cost estimates on highly experimental items such as core fabrication and reprocessing are merely guesses.



A simplified schematic of the reactor system. Rated plant output is produced with three of the four loops operating.

Those of us engaged in the design and manufacture of the PWR reactor can readily see how construction of this first plant will point the way to major reductions in both the capital and operating cost of later plants.

JOHN L. BOYER

are some 28 patents; he has received as many as eight awards in a single month.

Boyer has always displayed this facility in producing new ideas. In his undergraduate days at Rice Institute, he and several fellow students tinkered incessantly with a mercury-arc rectifier acquired by the college laboratory. They tried innumerable circuits, including an unsuccessful attempt to make the rectifier work as an inverter. This small sample of rectifier work whetted Boyer's interest sufficiently that when he finished the Westinghouse Graduate Student Course in 1942 he asked for assignment to the Rectifier Section in East Pittsburgh. He landed there just in time to get caught up in the mad rush to keep pace with the demands for rectifier equipment for the mushrooming aluminum and magnesium industries. Once this activity slowed from its torrid pace, Boyer turned to the design of high-voltage ignitron rectifiers and inverters and their circuits. His experience in the latter field led to his selection in 1945 as the author of the chapter on inverters in the *Industrial Electronics Reference Book*.

In 1946, Boyer was selected to head the Rectifier Development Section, whose primary responsibility is the development of new or improved rectifiers and their associated circuits. Here he has had ample opportunity to exercise his innate curiosity and his ability to produce and follow through on new ideas. Boyer immediately began a search for other and possibly better types of rectifiers. His group built and operated a cesium power rectifier. Then they tackled the older mechanical rectifier, to see if it could be improved. His section built and operated several experimental designs. It is worthy of note that in each case Boyer designed, built, and successfully operated a workable rectifier; these were no paper evaluations.

At about this time, materials engineers' patient efforts in the semiconductor field began to produce results. Boyer and his group set out to find practical ways to use these new materials in power rectifiers. This intense effort has now culminated in a practical, commercial germanium power rectifier in the middle-voltage range.

In casual conversation, nothing about Boyer's manner suggests the intensity and strong sense of urgency that prevails in his development work. Quiet, mild-mannered, and modest, he gives little outward evidence of the aggressiveness with which he pursues engineering development. That is, until the conversation rolls around to his activity; then you can readily sense his enthusiasm and imagination.

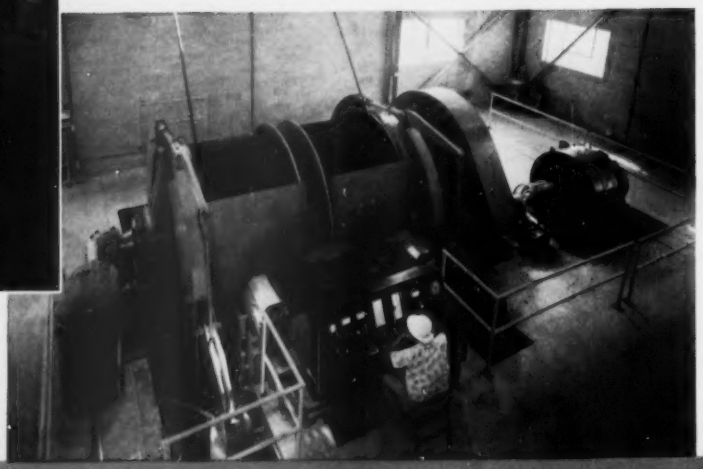
Boyer has the ability to appear unburried despite the pace of his activities. This was brought home to us again by his patience and cooperation in readying his article for this issue. From his calm, easy manner no one could have guessed that this was a man wrapped up in the million and one final development details of a new product, plus several other major development projects.

Boyer has an uncommon method of relaxing and getting the pressures of business off his mind. At one time he wanted to be an astronomer; even built his own telescopes and camera attachments to observe and photograph the stars. And although he finds little time to pursue it as a hobby, he claims it's the best way he knows to "get away from things." As he put it, "In engineering, you're always looking for new things to do, and trying to change things around you. For a change of pace there's nothing like relaxing and watching the stars go about their business, and realizing that there's nothing you can do to affect them one way or another." Sounds interesting.

In foreground is a trona-ore stockpile at the Wyoming site. In rear are the powerhouse, hoist house, ore conveyor, and crusher building.

Below, the powerhouse. In foreground are two steam-turbine generators; in background are high- and low-voltage switchgear and associated control-center equipment.

From Trona to



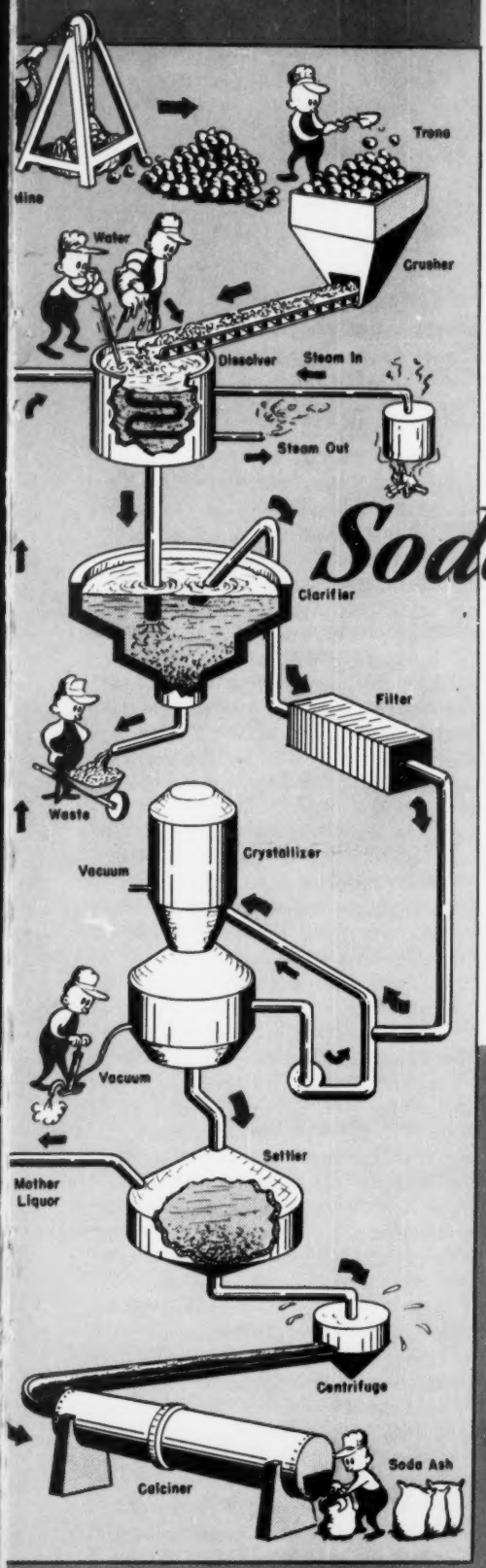
At right, the main haulage hoist. The hoist console is in the foreground and d-c hoist motor at right.

WHILE the magic of chemistry is a respected factor in our present industrial society, the extent to which it figures in manufacturing is not always appreciated. Take soda ash, for example; it is used across a broad section of industries. Glass making requires about a third of all soda-ash production. But it is also widely used in the manufacture of soap and detergents, textiles, paper, drugs and pharmaceuticals; in the production of aluminum and other metals, in sugar and petroleum refining, in water-softening compounds, and a whole host of other processes.

To accomplish this takes over five million tons of soda ash annually—which makes this compound the third largest chemical produced in this country. Over 90 percent of the soda ash is manufactured by an ammonia-soda process. The bulk of the remainder is produced from a new source of raw material located in Wyoming. The new raw material is trona, a mineral compound of anhydrous sodium carbonate and sodium bicarbonate. In its mined state, this compound is close to pure soda ash (Na_2CO_3), and is thus far simpler in terms of plant facilities and processing to convert to the pure product.

This trona bed is the only known deposit of its kind. The massive deposit—estimated at over 300 million tons—was discovered accidentally by geologists looking for oil in 1938. In the early 1940's Westvaco undertook research and development work to utilize this huge desposit—trona had never before been used for producing soda ash. This resulted in a commercial plant in 1952. The new plant is operated by the Westvaco Chlor-alkali Division of Food Machinery and Chemical Corporation, and jointly owned by FMC and the National Distillers Products Corporation. It is geared to produce 300 000 tons of refined soda ash a year—or about six percent of the total output of the country. This means mining about 600 000 tons per year.

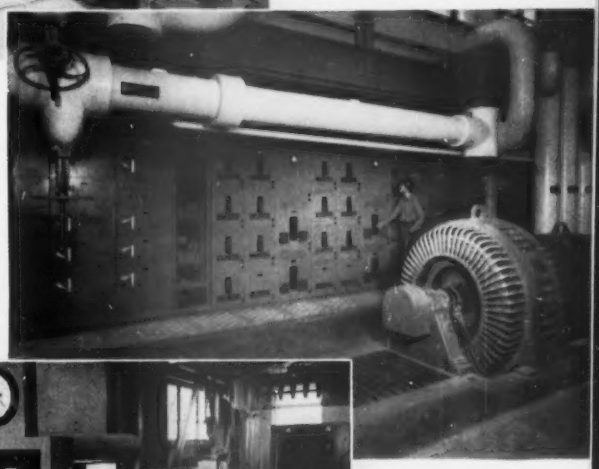
The trona seam averages about 10 feet in thickness, of which about 8 feet is high grade, and lies under several hundred feet of shale. Under the trona is about 20 feet of oil shale. The underground mining process in most respects resembles coal mining, and similar processes are used. The whole underground operation is highly mechanized. Ore is blasted out, and loaded by machine into shuttle cars. These shuttle cars are used only for the short runs to the nearest conveyor belt. The 36-inch belt conveyors carry ore to a crusher, which reduces the raw material to lumps under three inches in size. An automatic skip hoist carries the ore to the surface. This hoist is driven by a 500-hp d-c motor, powered by a synchronous m-g set. While the hoist is completely automatic, it can



Soda Ash

High-voltage switchgear underground at the 1500-foot level. Left to right are the shaft breaker, control, and the tie breaker.

Right, control centers, low-voltage switchgear, and mine-hoist m-g set. *Below,* turbine-generator console.



be controlled from a desk-type console, if desired.

The crushed ore that reaches the surface goes into storage piles. Basically the process of converting this ore to refined soda ash consists of removing metallic impurities, and getting the raw material into a form such that water and carbon dioxide can be driven off by heat. Essentially it is a purification process.

Rough ore is crushed to an extremely fine dust in an impact-hammer mill, then stored in a 150-ton capacity bin for use in the refining process. Powdered trona is dissolved in a set of three dissolvers in a mother liquor and water. The whole process is accomplished at about 200 degrees F (the boiling point at the altitude of 6200 feet). The hot, thick liquid is then pumped to "clarifiers" where the waste material settles out. Remaining traces of solid matter are removed by a series of filters. The clear liquid is then pumped to storage tanks, ready for the crystallizer. Throughout the process, the solutions are saturated and must be kept at nearly the boiling point.

The liquid proceeds to a vacuum crystallizer. By utilizing a vacuum corresponding to a temperature lower than that of the liquid, crystallization is brought about. This results in a crystal slurry, from which the clear liquid is drained off and returns to the dissolvers as a mother liquid, while the crystals remain for further processing. This takes place in a settling tank and centrifuge, then the relatively dry crystals are fed into calciners; at this stage the trona is actually converted to soda ash. The calciners remove excess carbon dioxide and water by heat. After complete drying, the finished soda ash is either shipped in bulk or bagged. The soda ash is then ready for any one of literally dozens of industrial processes, from the production of household detergents to metals.

Semiconductors

Their Characteristics and Principles

Electrical engineers have long considered materials as belonging to one of two classes—insulators or conductors. Actually an intermediate group, called semiconductors, exists; these unusual materials have rapidly proved a valuable part of the electrical family.

T. R. Lawson, Jr., *Materials Engineering Department, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania*

Seldom has any group of materials so quickly vaulted into a position of prominence, or so greatly aroused the imagination of the technical public as have the semiconductors, as exemplified by the transistor. On the other hand, the detailed mechanism of conductivity in semiconductors is not widely understood. Partly this may be due to their peculiar electrical properties—they are quite literally half conductor, half insulator; but another contributing factor is the unfamiliar electrical concept—that of the flow of "holes" as well as electrons—commonly used to describe the passage of current through the material. Semiconductors have other unusual characteristics, but considered on a fundamental basis, and nonmathematically, their operation is less difficult to follow.

The conductivity of semiconductor materials, as the name implies, lies between those of conductors and insulators. The resistivity range of semiconductor materials does not have sharp boundaries, but lies approximately between 10^{-2} ohm-cm and 10^{6} ohm-cm (for comparison, copper resistivity is about 1.7×10^{-6} ohm-cm and neoprene is of the order 10^{12} ohm-cm). But perhaps the most definite criterion of a semiconductor is its anomalous change in resistivity with temperature. Instead of increasing with temperature, as do most conductors, the resistivity of semiconductors decreases, i.e., these materials have a negative temperature coefficient of resistivity. The temperature range for which this behavior holds depends on the particular semiconductor and may not be room temperature. The Thermistor is an application of this property.

Another identifying factor is a scarcity of "free" electrons, common in conductors. Herein lies another distinction between conductors, semiconductors, and insulators. In a conductor, the outer ring of electrons in the atomic structure becomes a mobile matrix cementing the atoms together. The electrons in the matrix are free to move and provide a means of conduction. In a semiconductor or insulator, the valence electrons take part in a relatively stable bond between atoms. As will be seen, they are an integral part of the bound-together collection of atoms that constitute the material. Considerable energy is necessary to shake these electrons free of their atoms. One difference between a semiconductor and an insulator lies in how easily these valence electrons can be freed for conduction purposes. The energy required to break a bond in an insulator is large compared to the energy required in a semiconductor.

These three factors—conductivity between that of insulators and conductors, negative temperature coefficient of resistivity, and type and degree of binding force—are a few means of identifying semiconductor materials. Obviously, semiconductors are unique materials, with some characteristics of conductors, others of insulators, and some that are peculiar to themselves.

A fourth, and sometimes troublesome, characteristic of semiconducting materials is the extent to which their electrical properties depend on impurity content, method of preparation, and heat treatment. For example, while the resistivity of conductors is relatively insensitive to crystallographic imperfection and heat treatment, even minute variations in these factors have a drastic effect on a semiconductor's resistivity.

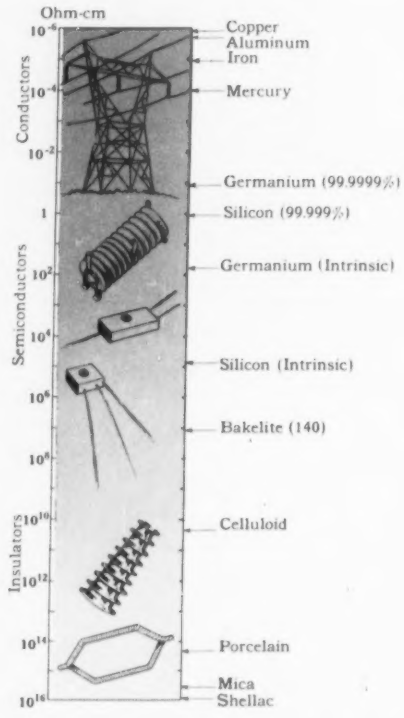


Fig. 1—This bar graph shows the relative resistivities of several different typical conductors, semiconductors, and insulators.

Methods of Conduction

Consider first the mode of conduction for a normal conductor, such as copper. The metals commonly used to carry electric current are formed from many almost identical crystals. These crystals are made up of atoms built together in a definite form. The mechanism of cohesion between these atoms (the "metallic bond") is not fully understood, but it is known that the electrons attached to the outermost orbit of each atom (valence electrons) become free, that is, they no longer belong to any individual atom. In any given metallic crystal, a certain number of free, or mobile, electrons for each nucleus are present in the crystal, approximately 10^{22} electrons per cubic centimeter. When an electric field is applied to this type of crystal, the mobile electrons are attracted or repelled, as the case may be, and move

with considerable rapidity. The ease with which electron motion occurs is represented quantitatively by two figures called the "specific resistivity" and the "mobility of electrons" in the material in question. Mobility need not be considered here, but more must be said about resistivity. The larger this figure becomes, the more difficult it is to pass current through the metal. Typical resistivities at room temperature are shown in Fig. 1.

Conduction in Semiconductors

In the so-called semiconductor materials, the mode of conduction and the order of resistivities obtained are entirely different. Whereas in the metallic conductor, built with the metallic bond, the valence electrons of each atom are freed for conductivity, in the case of semiconductors the valence electrons of the atoms are in relatively fixed bonding positions. They become an integral part of the structure of the material. A diagrammatic sketch of this difference in crystalline structure is given in Figs. 2 and 3. The ideal case as given in Fig. 3 is not obtained in nature. There is never a perfect combination of all electrons; some are always available for conduction. These, however, are present in very minute quantities as compared to a normally conducting material.

A semiconductor is not merely a poor conductor. For example, graphite and various resistor mixes (graphite and clay) are poor conductors but not semiconductors. Even such poor conductors have vastly more free electrons than semiconductors, and do not have a negative temperature coefficient of resistivity.

In a conductor, the valence electrons of each atom are not used in crystal structure and are so loosely connected to their respective atoms that even with the thermal energy present at very low temperatures they can be considered free, that is, no longer associated with a given atom. The resistivity of a conductor is largely determined by the degree of perfection of the lattice through which electrons move. In theory, a perfectly pure, flawless single-crystal conductor at a temperature of absolute zero, has zero resistivity. Departures from perfect periodicity in the lattice give rise to resistance to the motion of conduction electrons. Thus the thermal agitation of the atoms about their position of equilibrium leads to the increase of resistivity with increasing temperature.

Still another—and more unusual—method of conduction occurs in semiconductors. Nearly everyone has seen the game wherein a number of blocks are placed in a frame with one more space than there are blocks. The object of these games is to rearrange the blocks in a specific order by simply sliding the blocks and not removing any of them. The system used in the solution of these puzzles, if observed from a new light, illustrates that when a block is moved the space, or hole, is also moved. That is, even though the space has no mass, per se, it appears to move as the blocks, which do have mass, are moved. Again referring to Fig. 3, if an electron were missing from one of its usual positions in the crystal lattice, a "hole" would exist. Under the proper conditions, an electron from an adjacent bond may fall into this hole. The hole, of course, then appears in the space vacated by the electron. Since the material shown in Fig. 3 was originally electrically neutral, when an electron is removed from this lattice, the area from which the electron was removed shows a net positive charge.

The question naturally arises as to the source of these holes and electrons. At sufficiently low temperatures, each electron in a semiconductor is bound to an atom. At a higher temperature a few of the electrons are released from the parent atom by thermal agitation and are free to wander through the

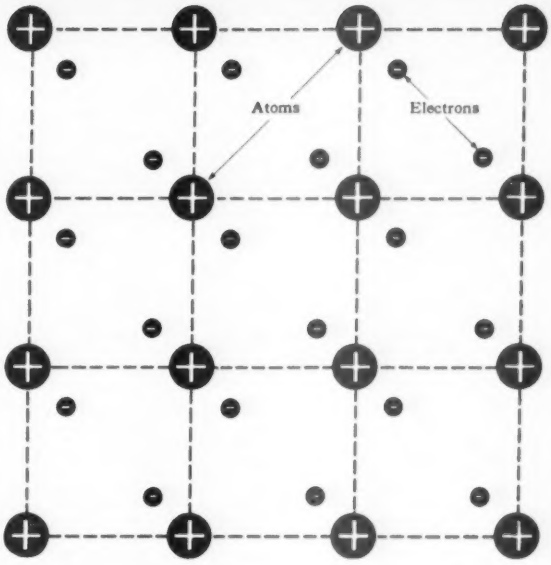


Fig. 2—In a metallic conductor, valence electrons are free to conduct as shown in this diagram of a typical crystal structure.

lattice in much the same fashion as electrons are released from gas atoms by ionization at extremely high temperatures. When an electron is removed from its normal place in a crystal structure by thermal agitation, it simultaneously leaves a hole in the crystal structure.

Electrons can be injected into a semiconductor by the simple expedient of attaching an electrode to the semiconductor and applying a negative voltage to this electrode. Somewhat more difficult to visualize, but the same process, holes can be injected into a semiconductor by attaching an electrode and applying a positive potential. A positively charged electrode possesses great affinity for electrons and attracts electrons in the vicinity of the electrode from their

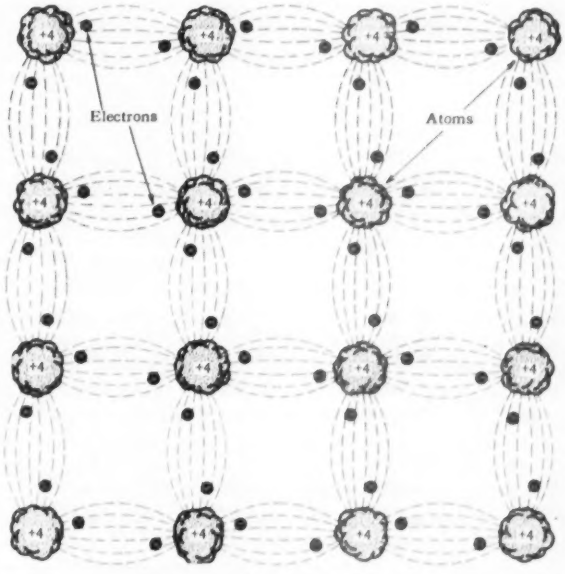


Fig. 3—In an ideal semiconductor, valence electrons are in relatively fixed bonding positions, and are not free for conduction.

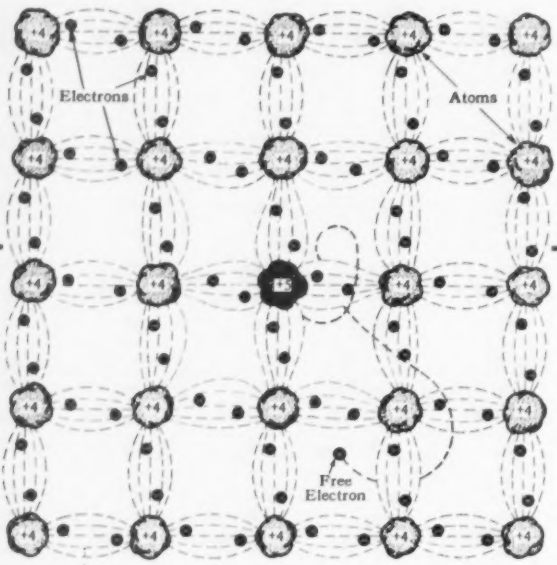
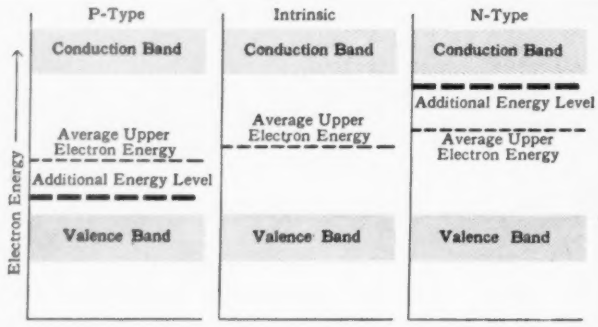


Fig. 4—When an arsenic atom is present in germanium, only four of its five valence electrons are used in bonding. The fifth is thus freed for conduction.



normal positions in the crystal lattice. Subtraction of electrons amounts to the same thing as the addition of holes, as long as electrons injected from the other electrode do not replace those subtracted. Therefore, a positive electrode can be used to inject holes in a semiconductor. As will be seen, this ability to add or subtract holes from semiconductors explains much of their usefulness in practical devices, such as rectifiers.

Holes in electrons can and normally do coexist in the same specimen of semiconductor. The number of each that exists at any time is governed by a mass-action law similar to that applying to chemical reactions. This is a case of dynamic equilibrium with electron-hole pairs being continually created by thermal agitation and destroyed by recombination.

Effect of Impurities and Imperfections

The considerations thus far have pertained to a pure semiconductor. Such a material does not exist. All practical semiconductors have quantities of several impurities. With impurity concentrations greater than about 0.001 percent, the semiconductor loses its characteristic properties and behaves more like a metal. However, when the concentration of the impurity becomes very minute, the quantity and identity of the impurity determine, to a startlingly high degree, the properties of the semiconductor. For example, by extrapolation the specific resistivity of pure germanium has been determined as approximately 60 ohm-cm. The presence of as much as 10^{-4} percent of an impurity may reduce the specific resistivity of the same germanium to less than 0.1 ohm-cm. Reference to Fig. 4 shows why this is so; here is depicted the presence of an arsenic atom in a germanium matrix.

Notice that arsenic has five valence electrons. Four of these are used in building the arsenic into the crystal structure of the germanium. The remaining electron becomes free for conductive purposes. Since extremely few conduction electrons exist in germanium at room temperature, the addition of even minute quantities of arsenic to germanium causes marked increases in conductivity.

When arsenic is an impurity in germanium, many free electrons are available for conduction. If an electric field were applied to this impure germanium, the resulting conduction would be due largely to electrons. Other elements having five valence electrons (such as phosphorous, antimony, and bismuth), when impurities in germanium, cause the same effect; these are called *donor* elements. Elements having only three valence electrons, when present as impurities in germanium, produce a deficiency of electrons—in other words, holes; these are called *acceptor* elements. Examples of these are aluminum, indium, and gallium.

Semiconductors, whose principal current carriers are electrons, are known as *n* (for negative) type conductors. Those in which the principal mode of conduction is by holes are known as *p* (for positive) type conductors. A very minute difference in the quantity of impurity may change the mode of conduction of a semiconductor from that of *n*-type to *p*-type or vice versa.

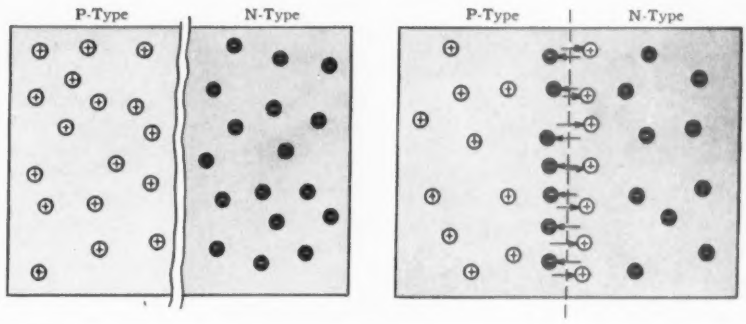
The usual process of preparing semiconductor materials for device work is first to purify the material to the highest degree possible. This material is usually—although optimistically—called intrinsic material; more accurately, intrinsic means 100 percent pure. A measured quantity of impurity is then added, just sufficient to produce the desired resistivity and conductivity type. This process of adding impurities is called doping, and the resulting materials are called doped semiconductors.

So far in this discussion of conductivity types, only principal current carriers have been mentioned. However, both types of carrier are present in a semiconductor even if it is predominantly *n*- or *p*-type. In an *n*-type semiconductor, the electrons are called the majority carrier and the holes are called the minority carrier. The reverse is true for a *p*-type semiconductor.

Although holes and electrons can coexist in a given semiconductor body, they eventually combine. The average time that a given free electron can exist in a semiconductor before combining with a hole is termed the lifetime of an electron. In many devices the useful lifetime of the minority carrier must be made as long as possible (several hundred microseconds, if feasible), since it is the change in minority carrier that alters the conductivity of the semiconductor. The surfaces of a semiconductor crystal contain defects that tend to foster the recombination of holes and electrons. Since it is desirable that holes and electrons exist separately for as long a time as possible, it is apparent that the number of crystal surfaces should be reduced as much as possible. This is done

Fig. 5—Donor atoms provide electrons of much higher energies than those in the intrinsic material, as shown in the *n*-type semiconductor. Acceptor atoms, on the other hand, provide energy levels for electrons only slightly above those in the intrinsic material, as shown in the *p*-type material at left.

Fig. 6—When an *n*-type semiconductor is in close contact with a *p*-type material, a net transfer of charge occurs. Electrons from the *n*-type material move to the *p*-type material until an energy balance is reached. This creates an electrostatic potential barrier, producing the rectifying properties.



by constructing semiconductor devices from single-crystal material. Producing large single crystals of uniform prescribed resistivity is anything but an easy job (see p. 182). Herein lies one of the major stumbling blocks in the wider use of semiconductor devices.

Faults in the semiconductor crystal also produce regions of high rate of recombination of holes and electrons. A high recombination rate produces a low lifetime of minority carrier. Thus a usable semiconductor not only must be a single crystal, but also that crystal must be as structurally perfect as possible. Lifetime of the minority carrier is a measure of the rate of recombination and, therefore, also a measure of the rate of generation of hole-electron pairs. Thus if the minority carrier lifetime is low, generation of hole-electron pairs is high.

The P-N Junction

The simplest junction device is the *p-n* junction—a crystallographically continuous union of an *n* and *p* region of a semiconductor. This has remarkable rectifying properties.

Reconsider the bond structure in a doped semiconductor. When donor atoms are present in the crystal, they provide electrons of much higher energies than those in the unexcited intrinsic semiconductor. Thermal agitation of the crystal at all ordinary temperatures is sufficient to ionize these electrons and thus provide free electrons for conduction. These electrons are in the so-called conduction band. This band is a range of electron energies; the energy levels of electrons free for conduction fall within this band. When acceptor atoms are present, they provide energy levels for electrons that are slightly above those in the unexcited state of the pure semiconductor. Consequently, thermal agitation of the crystal at all ordinary temperatures is sufficient to raise electrons from the unexcited state (or valence band) to the slightly higher impurity levels (see Fig. 5).

Visualize what occurs when the conductivity type of a semiconductor changes abruptly within a single crystal. In two materials in close contact, whose average upper energy levels are different (see Fig. 6), electrons move from the region of high electron energy to that of low electron energy. This transfer of charge continues until the electrostatic energy of the dipole built up within the semiconductor just balances the former difference in average upper electron energies between the two types of semiconductors. This results in an electrostatic potential barrier, which produces the rectifying properties of an equilibrium *p-n* junction.

As can be seen from Fig. 6, it is more difficult to move an electron by some external source from the *p*-type to the *n*-type region than the converse. Visualize what happens when electrodes are attached such that the *n*-type region is made positive with respect to the *p*-type region (Fig. 7). The potential barrier is thus made much higher. The electrons present in the *p*-type region will have to climb this potential hill in order to carry current into the *n*-type region. This represents a high impedance to current attempting to flow in this direction. On the other hand, if the *n*-type region is made negative with respect to the *p*-type (Fig. 8), the potential barrier is decreased and current flows much more easily.

Advantages and Limitations

Semiconductor devices can do almost anything that vacuum tubes can do—amplify, rectify, oscillate, limit, count, etc.—more efficiently and in smaller space. Reliabilities are expected to exceed gre tly those of vacuum tubes. Semiconductors are presently limited in frequency response and noise

Fig. 7—When electrodes are attached to the *p-n* combination in the manner below, the potential barrier is merely increased. This represents high impedance to current in this direction.

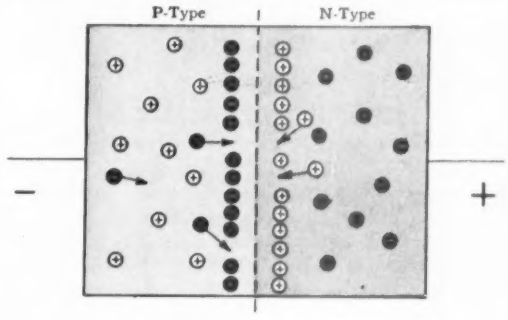
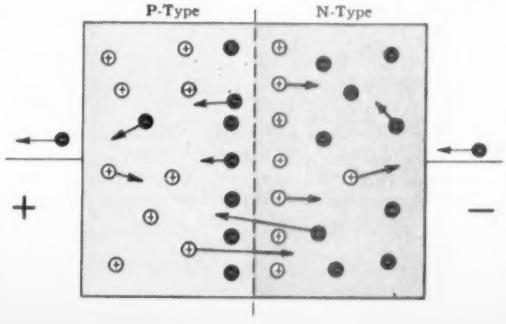


Fig. 8—When the electrodes are connected as below, the potential barrier is decreased, permitting current to pass.

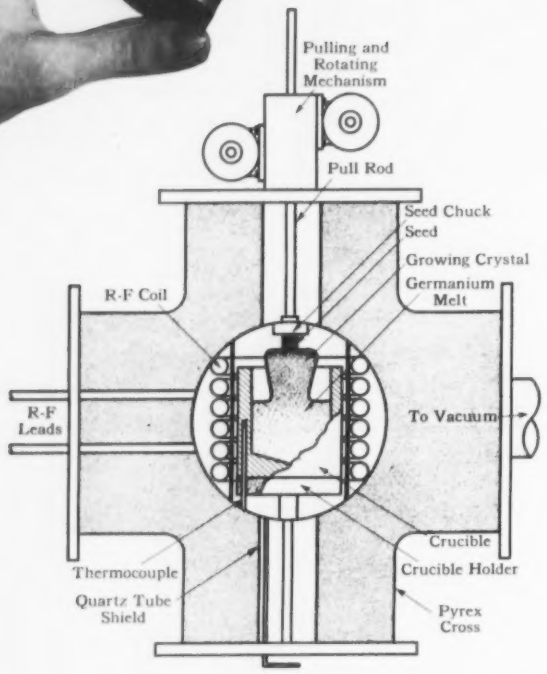


level, but improvements are being made continually in the directions of better design configurations, purer materials, and new circuitry. The problem of limitation on ambient operating temperature is being solved by the appearance of new devices perfectly stable to at least 150 degrees C.

Technological difficulties continue to hinder the development and manufacture of semiconductor devices. For one thing, semiconductors are extremely difficult to purify to the extent required for semiconductor devices. Most chemical purification procedures are considered successful if the resulting material is 99.9 percent pure. In a semiconductor device, a purity of the order of 99.99999 percent is required. In addition, nearly all new devices require the use of single crystal material, which is difficult to obtain. In many semiconducting devices precise control of geometries at the level of mils is required.

However, great strides are being made in the solution of the problems, as a brief review of current literature shows. The theory and application of semiconductors, while yet in its infancy, promises minor revolutions in the communications and power fields. On further development, such devices will change our concepts of electronic equipments.

Semiconductor Manufacture —Controlling the Infinitesimal



SEMICONDUCTOR materials suitable for rectifier use are not easy to come by. Purity is one main stumbling block. For example, germanium for rectifier use contains impurities in the order of only one part per 100 million. But to make matters worse, after working hard to make as pure a material as possible, an infinitesimal but precise amount of an impurity material—arsenic, for example—must be added to the semiconductor. In fact, these tiny amounts of impurities control the quality and type of semiconductor that results. As if these two requirements weren't enough, there's another—the material for a rectifier must be a single crystal, properly oriented and controlled in dimension.

Germanium goes through a number of preliminary refining processes to reach the "pure" state—the stage at which ultrapure refining begins. From this point on, engineers have to exercise their best ingenuity to remove impurities. They work on the principle that if you can't remove all the impurities from a given piece of material, perhaps you can at least herd them all into one small area—and then chop off that portion. To accomplish this, engineers make use of the fact that if you move a source of heat along a rod or bar of, say, germanium, melting areas of the bar successively from one end to the other, most impurities in the metal tend to follow along in the molten zone. In this fashion impurities are led into one end of the material, which can then be cut off, leaving purer metal.

Germanium for rectifier crystals is subjected to this sort of operation, first in a process called a normal freeze. Here the molten ingot is slowly withdrawn from a reduction melting furnace, allowing it to solidify from one end. The end that comes out of the furnace last, i.e., the last to solidify, collects many of the impurities. The material then is passed through a zone refiner, which melts successive areas of the metal along its length and draws most of the remaining impurities to one end. This renders germanium that has but one part per 100 million of impurities.

Now that the material is ultra-pure, a small amount (about 0.1 part per million) of an impurity is added to the material—arsenic, for example, to make it *n*-type, or indium for *p*-type.

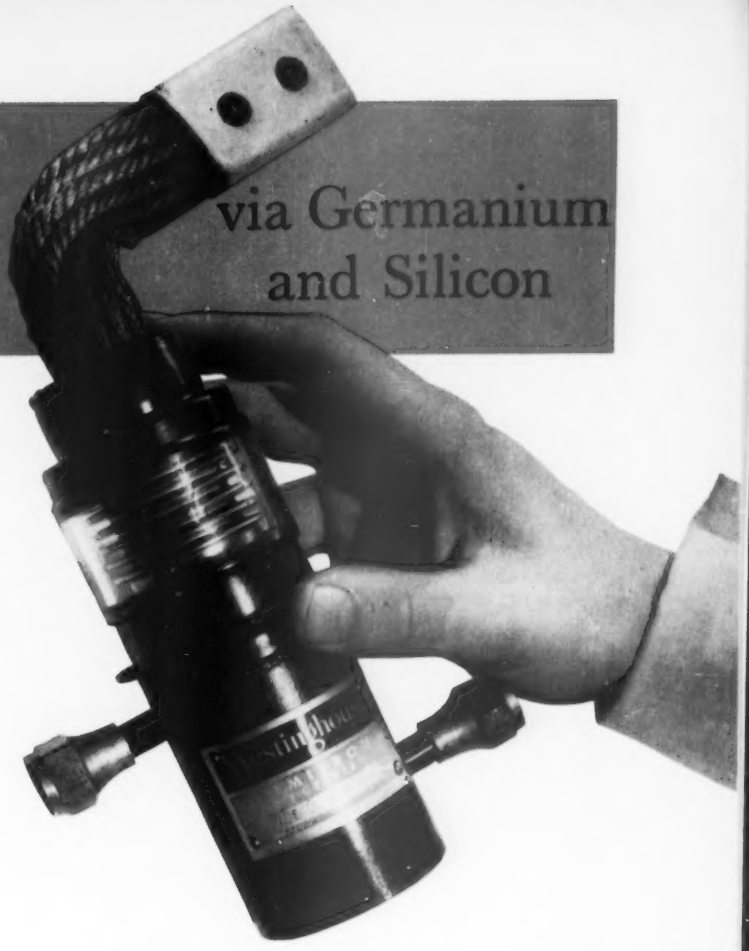
Next comes the difficult process of pulling a single, large crystal of pure germanium or silicon. Large, single crystals of many materials—sugar or salt, for example—are no particular novelty. Large, single crystals of germanium or silicon, even of random shape and size, are vastly more difficult to achieve; and the problem is further complicated by the fact that for rectifier use the resultant crystal must be precisely oriented, and reasonably uniform in resistivity throughout its length.

Crystal pulling makes use of a small, ultra-pure seed crystal of germanium. Pure germanium from which the crystal will be grown is heated to the molten state in a graphite crucible (see sketch of equipment at left). R-f heating is used and the whole process is carried out in a vacuum. The seed crystal is lowered into the molten germanium. When thermal equilibrium between seed and molten germanium is reached, the seed is slowly withdrawn and rotated at a constant slow speed. As it is withdrawn, a crystal is grown as molten germanium solidifies on the end. Silicon crystals are made in essentially the same fashion.

There are many variables in this process. Temperature, rate of withdrawal, and turning rate are all critical. Temperature must be maintained to within ± one degree at the operating temperature of 936 degrees C for germanium and 1420 degrees C for silicon. Too high a temperature melts the seed crystal; too low freezes the seed in the germanium. Smaller temperature variations cause undesirable results in the crystal. Slight changes in rate of turning or withdrawal produce a crystal with nonuniform diameter, as well as other undesirable qualities.

At present, single crystals as large as 1½ inches in diameter and several inches long have been grown (see inset photo, at left above). Such crystals are then sliced across the grain, either with diamond cutting tools or by other techniques. The resultant thin slice of the single crystal goes into a rectifier.

Power Rectification via Germanium and Silicon



JOHN L. BOYER
Manager, Rectifier Development Section
Transportation and Generator Division
Westinghouse Electric Corporation
East Pittsburgh, Pennsylvania

The burgeoning semiconductor art has produced a major new power device. It is the long-sought, efficient, high-capacity rectifier for low-voltage service.

OCCASIONALLY in a field of industrial equipment a gap exists in the range of available ratings—a gap that cannot be adequately filled by known devices. Such has long been the case with power rectifiers. Above about 200 volts, ignitron rectifiers have been highly satisfactory and efficient; below about 50 volts the selenium rectifier has been an able performer. But in the intermediate voltage range no rectifier has had all the desirable characteristics—high efficiency, low maintenance, and long life.

This gap has now been filled. Recent progress in semiconductor materials, namely, germanium and silicon, now make possible large-capacity power rectifiers in this middle-voltage range. A typical germanium power rectifier is shown in the photograph above. The present state of the art makes possible germanium rectifiers up to about 6000 amperes per unit with d-c voltages up to about 65 volts. Higher currents can be obtained by operating rectifiers in parallel. Voltages up to about 130 volts can be achieved by operating two units in series, and higher voltages by putting more units in series, although there is an economic limit. Rapid progress

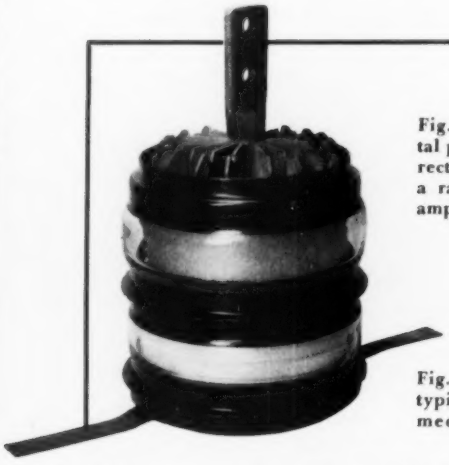


Fig. 1—An experimental pool-cathode cesium rectifier. This tube has a rating of about 200 amperes at 150 volts.

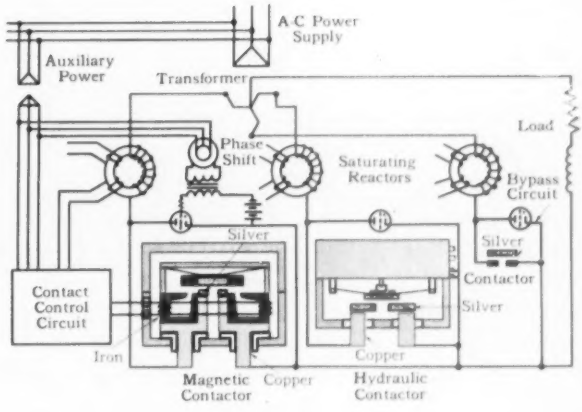


Fig. 2—This circuit is typical of those used with mechanical rectifiers.

is being made in the semiconductor field, and present limits are not likely to exist for long.

History of Low-Voltage Rectifiers

The gas-tube rectifier has been widely applied to higher voltages but is not economical below about 200 volts because the arc drop of practical tubes is virtually independent of terminal voltage and becomes a high percentage of the d-c voltage. For this reason ignitrons have not been applied below about 200 volts except in special cases. Considerable progress has been made in lowering the arc-drop of gas tubes to achieve high efficiency at low voltages. With mercury-arc rectifiers such as ignitrons and thyratrons, arc drop has been reduced and good efficiency can be obtained at voltages above 250. However, below 200 volts the tube loss is considered too large a percentage for power rectifiers.

Other materials, such as cesium and potassium, have been used in experimental tubes. Both hot-cathode and pool-cathode tubes using them have been made and tested in the laboratory. An experimental pool-cathode cesium tube with a current rating of about 200 amperes at 150 volts is shown in Fig. 1. The major advantage of the cesium tube is that low arc drops—between three and eight volts—can be obtained even at heavy current ratings. However, such tubes are very critical to operating temperatures and have low current ratings for the size of the electrode areas. Tubes of this type do not now appear to have as many desirable characteristics as semiconductor rectifiers.

The mechanical rectifier is old in principle, but considerable progress has been made in the last ten years. In this type rectifier, contact is made and broken mechanically each cycle to achieve rectification. Most of the progress has been in equipment to reduce the duty on the contacts, such as saturating reactors, which produce low current steps at the start and end of current conduction, and bypass low-drop tubes, which reduce arcing of the contacts. A typical circuit used for an experimental mechanical rectifier appears in Fig. 2. Various means for operating the contacts have been tried. The most satisfactory have been motor-driven and magnetic devices that close the contacts when current should be conducted and open them when the current has reached a low value. The contacts in a typical rectifier are closed by an electromagnet controlled by an auxiliary circuit that determines when the current conduction should start and end in each phase. Contacts are sealed in nitrogen at a pressure of five atmospheres to keep them clean and increase the open-circuit voltage they can support.

Even with special circuit means to electrically protect them, wear of mechanical-rectifier contacts leads to high maintenance. Even if additional improvement is made in mechanical rectifiers, they probably will not have the wide application that semiconductor rectifiers are expected to have in a few years.

Characteristics of Germanium Rectifiers

Because of the tremendous possibilities of semiconductor power rectifiers, a major effort has been made to develop them. The result is a new group of semiconductor rectifiers, called Semitrons. A practical Semitron using germanium as the semiconductor is now an accomplished fact.

The most important characteristic of the germanium rectifier is its low forward drop even with high current densities. The germanium Semitron rectifier is designed to take advantage of this characteristic; note the heavy current conductors and outlets for the concentrated cooling in Fig. 4.

Forward drop as a function of load current of a typical germanium Semitron is shown in Fig. 3. This Semitron has a rated load current of 200 amperes so that its forward drop is about 0.63 volt at rated load.

When an inverse voltage is applied to a germanium rectifier, a small amount of inverse current flows. The amount of current is dependent on the inverse voltage and on the temperature of the germanium. The variation of the inverse current with load current for a constant inverse voltage of 80 volts is shown in Fig. 3. The increase in inverse current with forward load current is due to the temperature rise of the germanium. The amount of inverse current that can be allowed determines the load that can be carried by the

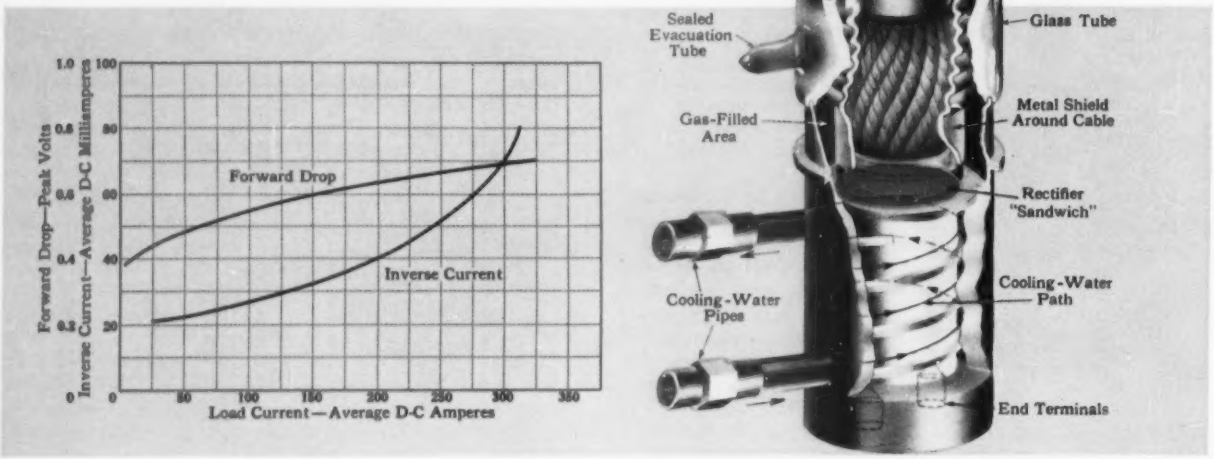


Fig. 3—Forward voltage drop and inverse current as a function of load current.

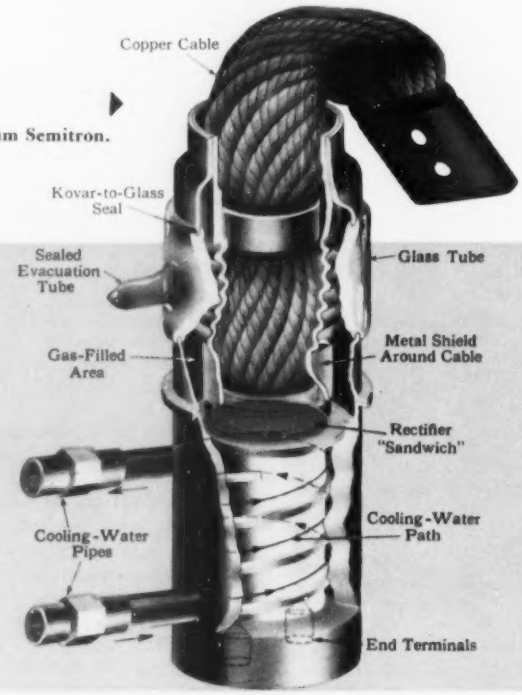


Fig. 4—A simplified sketch of the new water-cooled germanium Semitron.

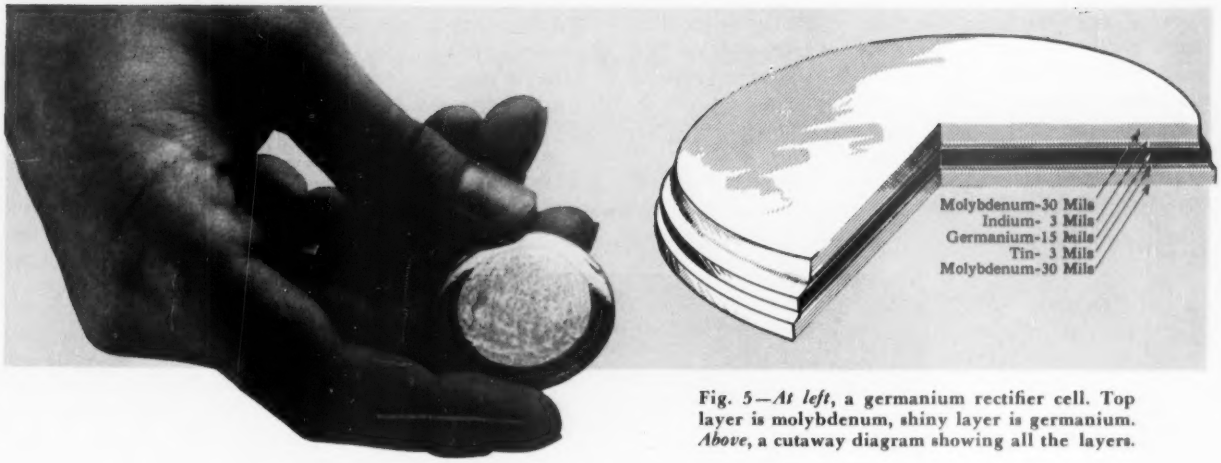


Fig. 5—*At left*, a germanium rectifier cell. Top layer is molybdenum, shiny layer is germanium. *Above*, a cutaway diagram showing all the layers.

Semitron. Since a small mass is involved, current rating is continuous and no overloads can be carried unless the base load is reduced.

Fault currents of power rectifiers are usually high, so special consideration must be given to both the forward and reverse fault-current capabilities of Semitrons. The forward fault-current limit of a 200-ampere germanium Semitron is about 3000 amperes for 10 cycles. Higher current or longer times cause permanent damage to the rectifier.

Fault current in the reverse direction through a germanium rectifier destroys the junction. Therefore, considerable care must be taken to see that the rated overvoltages are not exceeded for even a short time, and that germanium temperature is not allowed to go above about 65 degrees C.

Development of the Semitron

The heart of a germanium rectifier is a sandwich of five layers of material fused together (Fig. 5). Top and bottom layers are molybdenum, which has the same thermal expansion as germanium and has good heat conductivity. These layers provide strong stable support for the other layers during manufacture and provide good surfaces for attaching the electrical connections. The rectifying and center layer of the cell is a slice of germanium from a single crystal; this slice contains a small amount of impurity, which produces an excess of electrons and makes the germanium *n* type.* The germanium is soldered to the bottom molybdenum layer with pure tin and to the top molybdenum layer with pure indium. The molybdenum-tin connection is ohmic, but the indium on the top surface forms a *p-n* junction by diffusing into the germanium and changing its upper surface from *n* to *p* type. The Semitron is a heavy current rectifier, so a germanium crystal of about one inch diameter is used.

The crystal assembly is soldered to the copper base and flexible cable is soldered to the top molybdenum layer. The glass-Kovar seal is then placed over the assembly and the joints are welded vacuum tight. The Semitron is then evacuated and tested with a helium leak detector. After degassing the internal parts, a dry inert gas is sealed in the Semitron at a pressure of one atmosphere.

The heavy-current germanium rectifier is designed for a life of many years. To prevent cell failures due to moisture and other impurities, rectifier elements are hermetically sealed; they are also designed so that the crystal is not subjected to damaging mechanical forces—either from thermal expansion or from outside forces. Because of germanium's low operating temperature limit, the initial Semitron is water cooled, but the design is such that air cooling can be obtained with only minor modifications. Also, the rectifier is designed so that many units can be operated in parallel with relatively simple cooling systems.

Because of successful experience with glass-to-metal seals on tubes, this type of hermetic seal was chosen for germanium rectifiers. Early experience on small germanium diodes and transistors demonstrated the necessity of extremely good seals if long life is to be achieved. Moisture is one of the most deleterious impurities because it increases the reverse leakage current at the edge of the junction.

Germanium Semitron Units. Germanium Semitrons can be operated in power-rectifier circuits just as ignitron and selenium cells are. Since forward drop is very uniform in large germanium rectifiers, they can be operated in parallel without having to select the units. Semitrons can be operated in

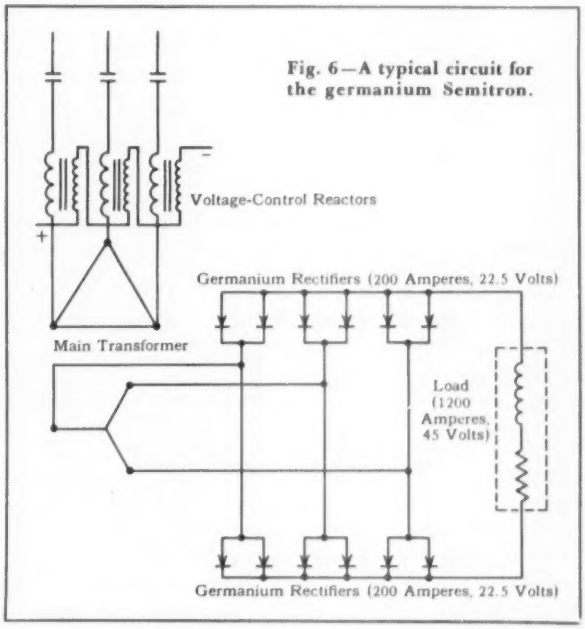


Fig. 6—A typical circuit for the germanium Semitron.

*For an explanation of *n* and *p* type semiconductors see p. 178.

series by selecting units that have similar inverse-current characteristics, but usually rectifier units are designed so that a definite voltage is impressed on each rectifier cell. Semitron rectifiers can be operated in parallel with other conversion equipment, such as ignitrons and m-g sets.

A typical circuit for a germanium Semitron rectifier rated 1200 amperes at 45 volts is shown in Fig. 6. Rectifier circuits have been made using as many as eight germanium Semitrons in parallel for each phase.

Fig. 7—*At left*, an experimental air-cooled silicon Semitron rectifier. Finned section is the heat radiator. *Above*, germanium Semitron rectifiers undergo laboratory tests.

Silicon Semitrons. Silicon is another semiconductor that offers great possibilities as a power rectifier. The major advantage of silicon is that it can be operated up to temperatures of about 180 degrees C. Higher inverse-voltage ratings can be obtained than with germanium, but at present a higher forward voltage drop—perhaps half a volt greater—seems likely with silicon. The development of silicon Semitrons has progressed to a point where experimental 200-ampere air-cooled tubes are being made and operated in the laboratory.

An air-cooled silicon Semitron is shown in Fig. 7. High-velocity air is forced up through the radiator to take away the heat, which is due mainly to forward load current. These silicon Semitrons can also be operated in parallel with a common air-cooled bus. Water-cooled silicon Semitrons can be used where there is a special reason that makes air cooling impossible or impractical.

Future of Semiconductor Rectifiers

Germanium and silicon rectifiers will find extensive application in the field of low-voltage power rectification from about 9 volts to about 130 volts d-c in the near future. As progress is made, the upper voltage limit will undoubtedly be raised to about 400 volts in the next few years.

At present the field of application of germanium rectifiers is in low-voltage electrochemical, electroplating, and some furnace supplies, and for low-voltage industrial power. When higher voltage silicon rectifiers are available, applications can be extended to medium-voltage electrochemical and to 250-volt industrial service. Germanium rectifiers probably will always be desirable for very low-voltage electroplating, because of their lower forward voltage drop.

In the long-range future, innumerable possibilities exist in the semiconductor field. For example, power transistors capable of carrying hundreds of amperes can probably be developed, which may lead to power rectifiers made as transistors to control as well as rectify the output voltage. Other possibilities look equally promising.

Because the possibilities of the new semiconductor rectifiers are so great, rapid progress is being made. The question of which germanium and silicon rectifiers should be put into production is difficult, because the designs become out of date before the units can be put into service. However, the excellent characteristics obtained in production units now indicate that semiconductor rectifiers will take over the medium-voltage field of rectification. The question then becomes one of how fast semiconductor rectifiers can be applied in other voltage fields. At the present rate of development, the semiconductor rectifier will soon find its way into many new applications.

• • •

New Tools for the Materials Engineer

A common question facing engineers engaged in development or production of alloys is: Within close limits, what are the constituents of a given alloy? The new way is to do it with a fluorescent x-ray spectrograph. A beam of x-rays is shot obliquely at a small wafer of the alloy. This produces secondary rays, each combination of wavelengths being characteristic of a particular element. The secondary-ray output is first separated by a grating crystal and then scanned through a 180-degree arc with a Geiger counter. The angle of the secondary ray identifies the element; the intensity—its amount. The method is accurate to about 0.3 percent for components existing in quantities of more than 5 percent in an alloy. A test is made in about 30 minutes. This method of analysis supplements the emission spectrograph, which is suitable for identification of small or trace amounts of alloy elements.

Transformer Insulation
. . . New Techniques . . . New Materials

No matter how well designed or constructed, no tool lives up to its fullest capabilities unless properly used. So it is with transformer insulation, where many advances have been made.

W. L. TEAGUE and L. B. RADEMACHER
Transformer Division, Westinghouse Electric Corporation, Sharon, Pennsylvania

THE LIFE of a transformer depends upon its insulation. Hence, the insulation design must have adequate margins for all voltage stress conditions that the transformer is expected to withstand in its normal lifetime. Another factor is the range and duration of temperature to which the insulation is subjected. Mechanical considerations are also important. Transformer insulation must support the weight of the windings, withstand shocks of shipping, and brace the windings against short-circuit stresses. Of these factors, the dielectric requirements present the greatest design problems, but thermal and mechanical requirements often dictate the arrangement of insulation and choice of materials.

The best insulation design from the standpoint of electrical stresses would be to completely enclose the winding in solid insulation. Conversely, since solid dielectric materials usually have poor thermal conductivity, the best design for cooling would be to reduce solid insulation to a minimum, and expose winding surfaces to the insulation cooling liquid. The best mechanical design requires materials of great mechanical strength, which often do not have the best dielectric properties. Hence, the insulation design, which is inherently complicated, is made more difficult by the design practices necessary in arrangement and choice of materials to meet the thermal and mechanical requirements.

In service, electrical stresses in a transformer are caused by the continuous dynamic voltage, short-time dynamic overvoltages, switching surges, and impulse voltages due to lightning. In a properly protected electric-power system, impulse voltages have ceilings determined by the protective devices, such as lightning arresters. Standardized low-frequency and impulse tests enable verification of insulation levels in the factory for the various system-voltage requirements. These tests give the design level for the winding. After this design level is established, a most important problem is to determine the impulse-voltage distribution through the transformer winding. Voltage distribution is determined by the winding

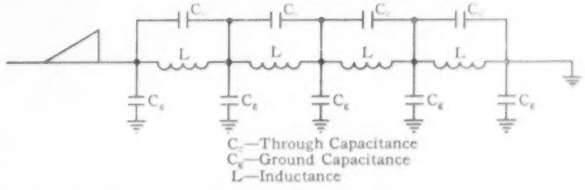


Fig. 1—Simplified sketch of winding capacitances and inductances.

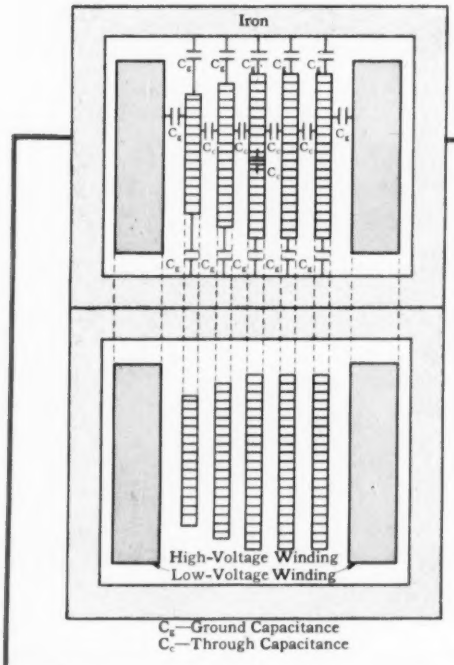


Fig. 2—Plan view of a shell-form transformer, showing winding arrangements and their associated capacitances.

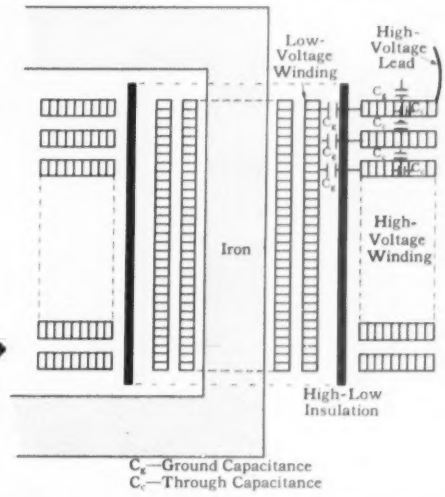


Fig. 3—Elevation view of a core-form transformer.

constants—capacitances, inductances, and resistances—which depend on design. Resistance, of course, is dependent on area and length of conductors; capacitance and inductance are determined by conductor size and length, number of turns, and the physical relation of each conductor to other conductors and ground. These relationships are shown in Figs. 1, 2, and 3 (p. 187).

The most important insulating materials used in liquid-filled transformers are oil-impregnated paper, pressboard, and mineral oil. Since these basic materials are moderate in cost, have excellent dielectric properties and are so reliable, few substitutes for them have been found. In dry-type transformers, where operating temperatures are higher and the insulation is not immersed in oil, synthetic insulating materials are more applicable. Hence, the major developments in transformer insulation have consisted of improving voltage distribution, applying insulation in new ways, improving the present materials, and in using new materials.

Voltage Distribution

Voltage gradients in transformers have been reduced by improving voltage distribution. Some improvements were accomplished by using winding arrangements that resulted in a more uniform voltage distribution through the winding, and others by developing means for controlling the dielectric field to avoid excessive voltage gradients.

Impulse testing has led to a better understanding of the reaction of windings to impulse voltages, and thus enabled improvement in voltage distribution. Basically, improving the voltage distribution in a transformer winding is a matter of increasing its capacitance through the winding, or of decreasing the capacitance to ground. The distribution in windings for shell-form transformers, which is inherently good, was made still better by the use of static plates, wider coils, and shorter groups. In core-form transformers similar measures of using static plates, static rings, and arranging and proportioning the windings resulted in significant improvement in voltage distribution. These measures decrease the concentration of voltage stresses between turns, layers, and coil sections near the line ends of the windings, and also reduce the voltage stresses from oscillations in the interior of

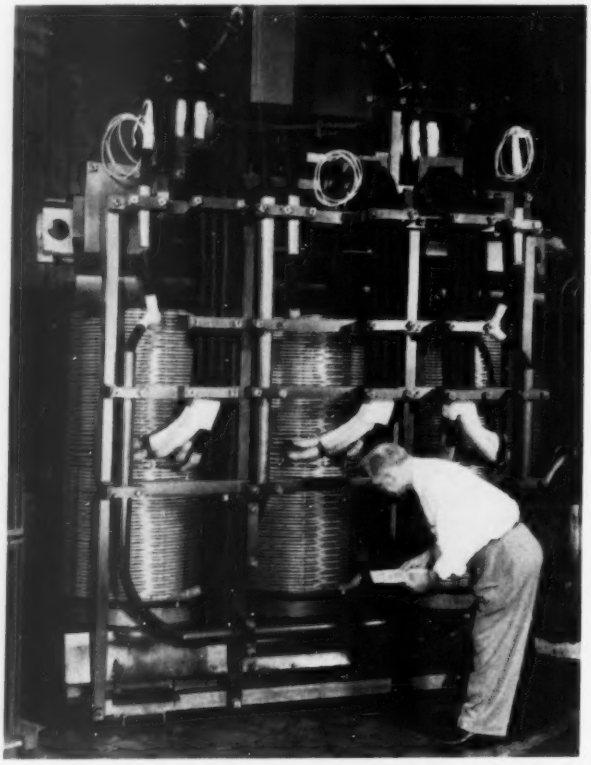


Fig. 4—A transformer with a high series capacitance winding.

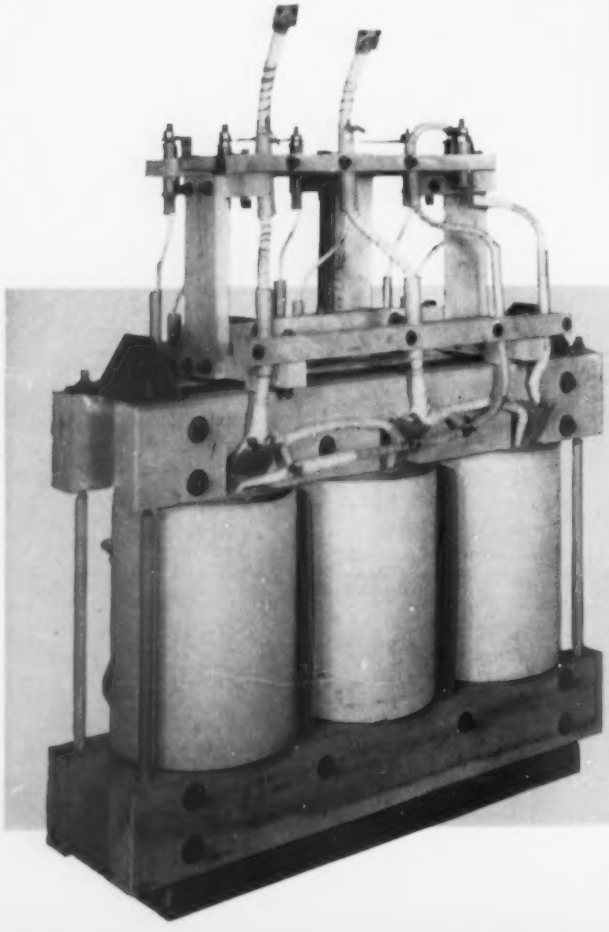


Fig. 5—A typical example of the Lowgrocap transformer winding.

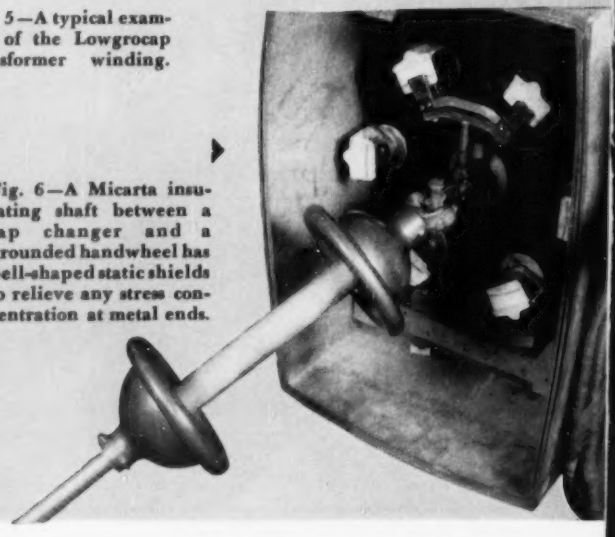


Fig. 6—A Micarta insulating shaft between a tap changer and a grounded handwheel has bell-shaped static shields to relieve any stress concentration at metal ends.

the windings. Two new winding arrangements known as the Hisercap[1] (high series capacitance) winding and the Lowgrocap (low ground capacitance) winding, result in a greatly improved voltage distribution. In the Hisercap winding (Fig. 4) this is accomplished by interleaving the turns to give a large series capacitance through the winding as compared to the ground capacitance of the winding. The Hisercap winding is particularly applicable to core-form transformers of the higher voltage classes, 92 kv and above. In the Lowgrocap winding (Fig. 5) the ground capacitance is reduced to a low value with respect to the series capacitance, resulting in a voltage distribution that is almost perfect. This winding arrangement is applicable to multi-layer cylindrical core-form coils.

Reducing the concentration of gradient at electrode edges to produces a more uniform electric field and hence a higher dielectric strength. This is a most effective method because it strives to make every part of the insulation structure take stress in proportion to its strength.

In a high-voltage, no-load tap changer, three different uses of this principle are made. The Micarta insulating shaft between the tap changer and the grounded handwheel has bell-shaped static shields with rounded edges (Fig. 6) placed at each end to relieve stress concentration at the metal ends and to produce a uniform field along the length of the shaft. During the past year, the working gradients at the rounded edges of these shields were further increased by forming crepe paper around them to get the effect of changing from bare to insulated parts. The second use of the principle of increasing strength by field control is the contact points on the tap-changer board. The edges of the metal contact points are rounded and raised above the surface of the molded deck to get the effect of oil jump and eliminate the high creepage stress across the surface of the deck (Fig. 7). Another example is the use of large-diameter insulated leads from tap-changer points to windings to avoid the high stresses in the tape or oil that would occur with small leads. Where current-carrying requirements are small, an insulated cable with rope center and stranded copper periphery provides a larger diameter and resulting lower gradients.

Another example of dielectric field control is the stepping back of line coils at the end of the coil groups for high-voltage shell-form transformers (Fig. 8). At the corner of coil groups, total stress is a combination of that resulting from coil-to-coil voltage and coil-to-ground voltage. Stepping the static plate and line coils back slightly produces a rounded effect, rather than square corners, at the end of the coil stack; by this method, the concentration of stress in a vital portion of the insulation structure is decreased.

An excellent way to eliminate high dielectric-stress concentration at an electrode is to surround it snugly with an insulating material of higher dielectric constant than is used in the more uniform portions of the field. For ideal conditions, the dielectric constant should be such as to cause the maximum gradients in the insulating materials used to be proportional to their strengths. An example of this is the corner channels used around shell-form coils. These were recently modified to use crimped pressboard. The new channels are more flexible and can be fitted more closely to the coils; this results in a stronger insulation structure. In many applications, such as for insulation on leads, static plates and rings, and the coils of high-voltage instrument transformers, crepe paper is used to control the dielectric field. Because of the elasticity of crepe paper, it fits closely to the electrode, reduces voids, and produces consistent characteristics.

Insulation Arrangement

To obtain the maximum impulse strength in a transformer winding, insulating barriers should be placed perpendicular to the lines of stress or parallel to equipotential surfaces.[2] Although practical problems are often encountered in applying this fundamental principle, numerous improvements have been made in insulation arrangement to conform more closely to it. In core-form transformers, the insulation between windings and between windings and ground is interleaved with angles to approach the equipotential surfaces. In shell-form transformers, the windings are boxed in with pressboard sheets, channels, and angles (Fig. 9) in high-stressed areas so that stress lines are perpendicular to insulating sheets, to avoid the tendency of the high voltage to creep along the sheets. These principles are also followed in designing pressure plate insulation, boxing in leads, and in locating barriers around high-voltage parts.

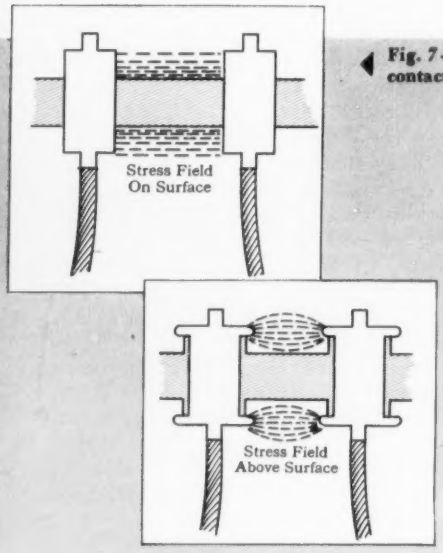
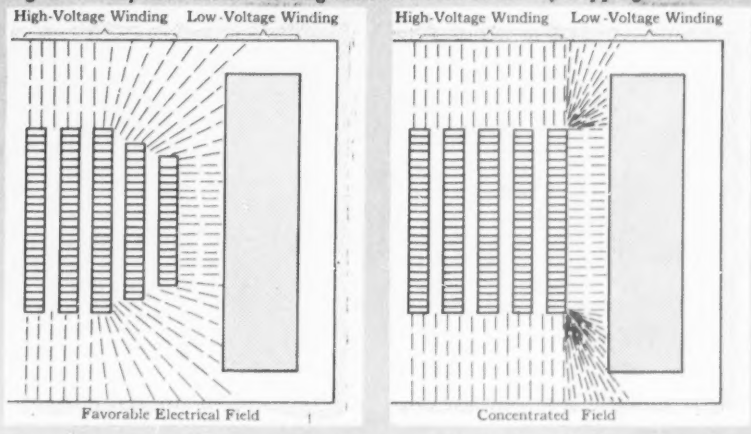


Fig. 7—These show field control effected by raising the metal contacts of a tap changer above the surface of the molded deck.

Fig. 8—A simplified sketch showing dielectric field control by stepping back coils.



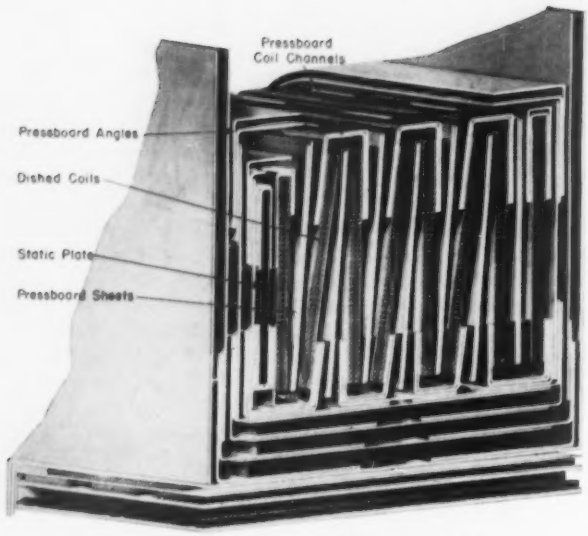


Fig. 9—A cross section of a shell-form transformer through one coil group, showing coil arrangement.

To get more insulation in the highly stressed ducts between coil sections and still keep the through capacitance large to avoid poor voltage distribution in the winding, dished coils (Fig. 9) are used. This arrangement allows greater insulation between the two coil edges having greatest potential difference, while the edges at the same potential have a minimum insulation. In this way, the impulse strength between coils is increased without a resultant increase in impulse stress due to a poorer voltage distribution in the winding.

Another example of improved design is high-voltage oil-impregnated instrument transformers. Similar construction is used in both current and potential transformers for voltages of 69 kv and above. The high-voltage coils of current transformers are heavily taped with crepe paper to get solid insulation, rather than oil, in intimate contact with the coil; this reduces the gradient at the edges because of the high dielectric constant of the tape. The tape serves as insulation between coil sections and, in combination with pressboard, as insulation to the low-voltage winding and ground. Another feature is the combination of the bushing with insulation to ground. The bushing insulation is largely crepe paper enclosed in a porcelain shell. To reduce the gradient in the crepe paper, a smooth metal tube of proper radius is placed over the line leads. Then a specially shaped shield taped with crepe paper is placed next to ground at the bushing flange. The crepe paper that forms the bushing insulation is interleaved with that on the coils to be continuous with the ground insulation. In this way, high-voltage coils form the high-voltage element and are roughly spherical, much like a bushing ball; this avoids sharp points that result in concentration of voltage stresses. The complete transformer and case is only slightly larger than an ordinary bushing of equivalent rating placed in a tank of oil. The shields can be shaped, the radii of the edges and the lead tube selected, and the insulation arranged so that all parts of the insulation take their share of the load.

Insulating Materials

Improvements are continually being made in the basic insulating materials. Average power factor of pressboard has been decreased more than 25 percent by careful study of the problem and resultant process changes to effect better control. Crepe paper now has a crimp that makes the tape more uniform, especially on curved surfaces, less spongy, and hence more consistent in dielectric strength. A paper treated with thermosetting varnish is used for turn-to-turn and layer-to-layer insulation. As turn insulation, it gives a rugged, strong coil without a varnish dip. As layer insulation, it holds each wire in place in the layer. Varnishes have been developed that have better oil resistance. Wire enamel has been developed with twice the scrape abrasion resistance of the older enamel. Because of this enamel, in many applications paper tape is no longer required as an insurance against bare spots. This wire also gives a better space factor and smaller windings.

The quality of transformer oil—i.e., its dielectric strength and power factor—has been improved by a more systematic and rigid testing program and extra care in handling and storing. Each shipment of oil is checked for dielectric strength, power factor, and other qualities before the oil is placed in storage tanks. Dielectric strength of oil in tanks is checked every day; power factor, as well as other characteristics, is checked weekly. Inhibited oil is now generally used in distribution transformers to minimize deterioration. Inerteen has been improved by the addition of a scavenger, which improves its arc-resistance properties.

Molded insulations from thermosetting plastics have been improved. Examples are molded cleats for use in reactors and molded no-load tap-changer decks. Through better processes, voids are eliminated and insulating parts with more dependable mechanical and electrical strengths are obtained. The characteristics of laminated plastics have also been improved. Power factor of Micarta boards has been cut in half through better control of moisture, use of a new, low power-factor resin, and production power-factor measurements. Micarta tubes, such as those used for tap-changer shafts, are cured under pressure to eliminate air films and to obtain increased and consistent creepage strength. In some cases this permits shortening the shaft, and thus the overall transformer height.

Better methods and control in drying, impregnating, and vacuum filling have increased and made more consistent the dielectric strength of cellulose and oil insulation. More rigid and systematic use of resistance and power-factor tests has been effective in controlling the quality of drying. Large transformers are dried in their own tanks by forced circulation of hot air through them. This process allows the unit to be covered with oil in minimum time. The impregnation and filling of instrument transformers with gum by alternate pressure and vacuum cycles[3] has been effective in eliminating trapped air, thus assuring consistent dielectric strength.

The insulation for outlet condenser bushings now uses a low-loss, high-dielectric-strength paper thoroughly impregnated in oil. Both the upper and lower ends are enclosed in porcelain. The bushing is filled by an elaborate process with degassed oil and is then sealed. The insulation in this bushing meets the exacting triple requirement of good mechanical strength, low thermal gradients, and high dielectric strength with very little maintenance in service.

A number of newly developed insulating materials, and new applications of older materials, have been used in dry-type transformers. Some have also been applied in oil-insulated transformers.

Polyvinylchloride insulated wire is being used for control-circuit wiring, largely because it is pliable down to minus 40 degrees C, and has high scrape-abrasion resistance. Other advantages are high dielectric strength, thermal stability, and the fact that it can be used in air or oil. A similar material is

an extruded tubing, used on leads of distribution transformers. This has 25 percent greater dielectric strength than the previous material.

Polyester glass materials made from glass-fabric laminates or from glass mat are now used for duct spacers, terminal boards, and filler materials in air-insulated transformers. A recent application of polyester glass laminate is a molded shell to insulate the winding of an air-insulated, ring-type current transformer from the core, and to serve as a cushion pad on which to wind the enamel wire. Mylar, a polyester film, has been used in small amounts for insulating a thermostat in a load-indicating device. Fosterite, a polyester resin introduced during the last war, is used to encase small specialty transformers. The moisture resistance of Fosterite makes it especially suited for this type of equipment, and eliminates can-type enclosures and bushing seals.

Silicone insulating materials are being applied to air-insulated transformers in increasing amounts. These materials include silicone varnishes and paints, silicone-treated glass cloth and tubes, silicone-treated asbestos, glass-silicone laminates, and silicone-bonded mica sheet. The favorable characteristics of these materials are their thermal stability, moisture resistance and good electrical properties. At present their apparent disadvantages are cost, high curing temperatures, and involved curing processes. Wider usage will likely overcome these disadvantages.

An example of the use of silicone insulating materials is the relatively new sealed dry-type transformer (Fig. 10). The disadvantages of silicone are offset by the high degree of safety in transformer operation, and extremely low maintenance costs. Since the high-temperature insulating materials used in this transformer are air, porcelain, glass, and silicone, it will give satisfactory service at winding temperatures in the order of 200 degrees C. The conductor insulation is glass fibers treated with silicone varnish. The insulating tubes for the windings are made of glass cloth treated with silicone varnish. The core-and-coil assemblies of these units are coated with silicone varnish. Since the sealed dry-type transformer was developed, more than 200 units in ratings of 100 to 1500 kva and voltages up to 15 kv have been placed in operation.

Silicone-impregnated materials are also used in dry-type distribution and instrument transformers, and small aircraft transformers. In general, silicone glass or silicone mica is used. In some applications, use is made of silicone-impregnated asbestos sheets or boards. By using a silicone laminated-glass tube in a through-type current transformer and dipping the core and coil in silicone varnish, the current transformer is suitable for outdoor applications.

Summary and Trends

For oil-insulated transformers, the greatest progress in insulation has been in arrangement of insulation and improving the quality of proved existing materials; only a few new materials have been added. Paper and pressboard used in mineral oil are so satisfactory that no moderate-cost substitutes with better properties have been found.

In dry-type apparatus, which is inherently for low-voltage applications, many improvements have resulted from the use of new materials with high thermal stability and good dielectric properties. These materials have also enabled reduction in size and weight of dry-type transformers and an increase in the thermal operating range. At present, full utilization of synthetic materials is not possible because of the relatively high cost and high processing temperatures.

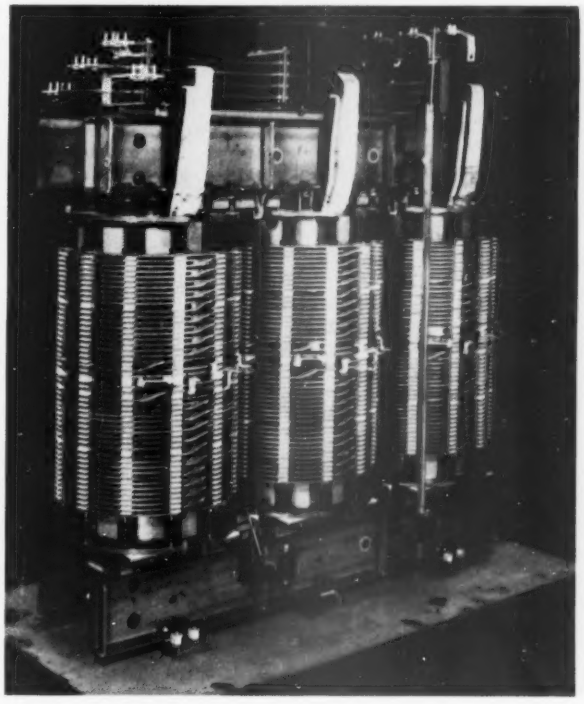
Tests indicate that a practical vapor-insulated and vapor-cooled transformer is possible by making use of high-molecular-weight fluorocarbons. These liquids are chemically inert and thermally stable. This scheme involves the use of the heat of vaporization of the liquids for cooling and the dielectric strength of the vapors for insulation. Such a transformer would combine many of the advantages of liquid-immersed and dry-type transformers.

As transformer insulation, system design, and protective equipment have been improved, there has been a trend toward lower than standard insulation levels that may affect the insulation of transformers. For many years on solidly grounded systems, 138 kv and above, transformers with insulation one class lower than standard have been successfully used. This experience led to investigations[4] that showed that, on high-voltage well-grounded systems with 75-percent lightning arresters, insulation levels can be reduced to one and one half voltage classes lower than standard. These reduced levels have been used in systems 230 kv and above. There is some tendency to reduce the insulation levels to still lower values. Should this come about, other factors, such as the continuous normal low-frequency voltage, abnormal dynamic voltages, switching surges, and radio-influence effects may require special consideration in the insulation of transformers.

REFERENCES

1—"Improved Core-Form Transformer Winding," E. J. Grimmer, W. L. Teague, *AIEE Transactions*, Vol. 70, 1951, p. 962.
2—"Surge-Proof Transformers," H. V. Putman, *AIEE Transactions*, Vol. 51, 1932, p. 579.
3—"Recent Improvements in Theory and Practice of Vacuum Plastic-Filled Insulation for Voltage Transformers," E. C. Wentz, F. B. Colby, *AIEE Transactions*, Vol. 71, Part III, 1952, p. 358.
4—"Transformers and Lightning Arresters—Tidd 500 Kv Test Lines," F. A. Lane, J. K. Hodnette, P. L. Bellaschi, E. Beck, *AIEE Transactions*, Vol. 66, 1947, p. 1613.

Fig. 10—A sealed dry-type transformer with silicone insulation.



What's NEW

Transistorized Power-Line Carrier

TRANSISTORS are invading the power-line carrier field. Completely transistorized carrier equipment is now being tested by Westinghouse on Potomac Edison's system. The equipment is designed for telegraphic functions, such as relaying and telemetering. The transmitter consists of a master oscillator, buffer amplifier, and output amplifier; the receiver has high-frequency amplifier, detector, and relay-operating stages. Both point-contact and junction transistors are used. Expected advantages, in addition to compact design, are long trouble-free life, and elimination of the need for filament-heating power. Additional assemblies for voice communication and other uses are to be tested in the near future. However, commercial models of transistorized carrier equipment will not be made until test results have been fully evaluated.

A Leak-Tight High-Vacuum Valve

RESEARCH at the extremes of physical conditions brings problems that are never thought of in ordinary technical practice. For example, what does one use for vacuum valves at pressures as low as 10^{-10} millimeters of mercury? Each time the ordinary ground-glass stopcock is opened and closed, the grease used in it may give off thousands of times more gas molecules than are originally present in the entire system. In ultrahigh vacuum systems, it is necessary to eliminate all such lubricants and to obtain a valve that can be degassed at high temperatures.

The new valve consists of a heavy cup of copper with a one-fourth-inch diameter hole in the center. Silver-brazed to this cup is a thin, flexible diaphragm containing a plunger of Kovar. The nose of this plunger is chamfered and highly polished, and when forced in by a screw forms a seat in the copper cup, thus closing it. Because the hard metal shapes the copper seat to its own contour, it makes a molecularly tight enclosure. Since the all-metal valve can be degassed at temperatures as high as 450 degrees C, the amount of gas given off upon opening and closing it is less than 1000th as much as that given off by old-fashioned stopcocks.

Harder Gears for Big Ships

A MAJOR STEP has been achieved in the hardness of the rims of the big gear wheels used on heavily powered vessels. High hardness can be obtained on smaller wheels, but vessels like the U. S. S. *Forrestal* require bull gears with single-piece forged rims more than 13 feet across and built-up centers. Such wheels are fabricated by arc welding and then stress relieved, which reduces hardness.

New techniques, using low-hydrogen electrodes, which give sound welds with molybdenum-vanadium steel, have resulted in hardness of tooth surface between 223 and 269 Brinell—mostly the upper figure—which is well above the usual range of 160 to 190. It is believed that still higher hardnesses can be obtained after further development.

A Precision, Radio-Shielded Laboratory

RADIO WAVES are insidious. To build a room that shuts them out entirely borders on the impossible. To build a shielded room for radio-influence testing in which outside radio frequencies are cut down by one half or two thirds is comparatively easy. A few rolls of screen wire, a little care, and a few hundred dollars will achieve that. But to reduce outside signals to, say, one percent calls for a precision-built laboratory and about $10 000.

Such a room has been provided the East Pittsburgh laboratories. It is 20 feet by 16 feet by 9 feet high. It has a double wall, with heavy, sliding-contact doors. Because it is virtually air tight, air conditioning is essential. The air ducts have carefully designed baffles to filter out unwanted frequencies. It is even necessary to avoid tacks and nails, because the points become antennas to carry signals through the screen into the room.

With the advent of television and the stiffening regulations of the Federal Communications Commission, electrical apparatus of all kinds must be more carefully designed not to produce interfering signals. This room will help to that end.

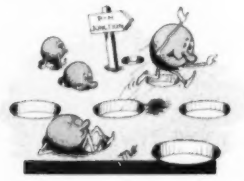
Longer life, additional cooling, and stronger construction are features of a new series of Life-Line loom motors. Finned cast-iron end brackets increase strength and reduce motor temperature. Oversized bearings and a special grease give longer life.

Rapid-response magnetic amplifiers control the stand and reel drives of Pittsburgh Steel's new tandem cold-strip mill (*right*). A 400-cycle Magamp system is the key element, since response of a Magamp to an error signal is inversely proportional to supply frequency. Each mill-stand drive consists of two motors, one for the upper work roll and one for the lower. Each motor pair is supplied by its own d-c generator. A reference bus serves as a common reference for all stand generators. Differences between reference and generator voltages cause a control Magamp to send a corrective signal to a power Magamp, which in turn adjusts the generator field and thus restores motor speed to the desired value. Tests indicate the response is about 0.1 second, with practically no overshoot.

Personality Profiles

For a man but four years out of college, *T. R. Lawson, Jr.*, has had a diversified career. After graduating from the University of Buffalo in 1950 with a B. A. in chemistry, Lawson worked for a time in the quality control laboratory of an automobile manufacturer. Next, he joined an electrical concern, where he helped develop finishes.

Lawson came to Westinghouse in 1952 as a member of the Semiconductor Development Section of Materials Engineer-



ing. Here he is concerned with the fabrication of experimental semiconductor devices. At first glance this may seem an unusual spot for a chemist, but in reality a major portion of semiconductor work has been in solving materials problems.

For his recreation, Lawson "tinkers around" in a fairly complete electronics lab in the basement of his home. He also takes an active part in several choral groups, one of which he conducts. The musical interest covers a wide scope; he is a member of a small group of spare-time jazz musicians, who gather at irregular intervals for "jam sessions." Last year he and another electronically inclined musician recorded a number from the session on a tape recorder; then the group rerecorded on top of the original piece with the members doubling on a second instrument. Opinions vary as to the result. Lawson is relatively noncommittal; "It was an interesting experiment" is the most you can extract from him.

• • •

Charles H. Weaver is a young man (40) in a big job—manager of the Westinghouse Atomic Power Division. But his direction of one of the toughest engineering projects thus far in the atomic age should leave little doubt that age is no criteria by which to judge accomplishment.

Weaver's rise in the Westinghouse Corporation has been rapid. An electrical engineering graduate of the University of Pennsylvania in 1936, he spent two years on the Graduate Student Course, then joined the sales department of the Transportation and Generator Division. After two years here he transferred to the marine section as a sales engineer, became section manager in 1943, and later the same year was appointed manager of the marine department. By 1945 his activity included the combined marine and aviation sales departments. Three years later he became industrial manager of the central sales district of the Company and in 1948 assumed his present position.

Such rapid movement upward is obviously based on firm foundation. Weaver is aggressive, an able administrator, and is equally at home with the problems of private industry or those of government-industry relations.

In his position, decision-making constitutes a major part of his efforts. Perhaps in this Weaver displays another reason for his rapid success; though his schedule is always overloaded, Weaver sits quietly listening to both sides of a question, interrupting only to have a point clarified, or to get the discussion back on the track, which he does with great facility. When the facts are in, Weaver has his decision ready, along with sound supporting reasons. No vacillating, no jumping to conclusions.

• • •

Dr. William E. Shoupp has the rare facility of being able to talk nuclear physics on equal terms with either fellow physicists or high-school students. And he does either with great skill. This ability comes naturally to Shoupp; but it likely was enhanced by the six years he spent as a graduate assistant and physics instructor at the University of Illinois. A physics graduate of Miami University of Ohio, he obtained his M.A. (1933) and Ph.D. (1937) at Illinois.

Shoupp has been an avid atom researcher since his graduate school days. Shortly after he joined Westinghouse as a Research Fellow in 1938, he was placed in charge of the newly completed Van de Graaff generator. While experimenting here he and several of his co-workers discovered photo-fission. In 1941 he became a research scientist, and two years later was appointed manager of the electronics department of the Research Laboratories. This activity broadened to include all nuclear physics work.

During World War II, Shoupp shuttled between work on the atom-bomb project and on radar; in both fields he made notable contributions. After the war he returned to basic research with the Westinghouse atom smasher. But in 1948, when the Atomic Power Division was formed, Shoupp was chosen as its director of research. Here he has played a prominent part in the development of the nuclear-power plant for the *Nautilus*.

At present the Atomic Power Division is up to its neck in the development of the nation's first central-station nuclear-power plant. Judging from past performances, Shoupp, now assistant manager in charge of development, will play an important role in its progress.

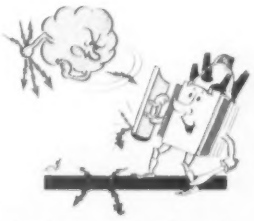
• • •

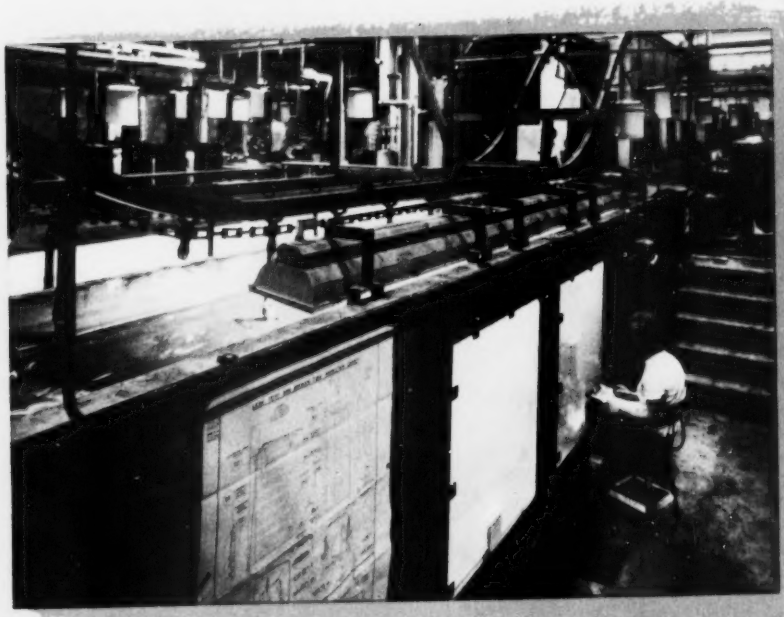
Thirty-two years ago *W. L. Teague* got a leave of absence from the University of Arkansas, where he had been teaching, to come to Westinghouse to acquire some industrial experience. He's still here. And he's still acquiring that experience he was seeking. Fortunately, Teague is as able at teaching as he is at absorbing knowledge; he has a well-deserved reputation among transformer engineers for his helpfulness and willingness to lend a hand with knotty technical problems.

An electrical-engineering graduate of the University of Arkansas, Teague came to Westinghouse in 1922 as an oscillograph operator in the Materials and Process Engineering Department in East Pittsburgh. In 1923 he transferred to Transformer Engineering, and has since been closely associated with many developments in the power-transformer field, particularly high-voltage insulation.

Teague, now manager of the Insulation Development Section, has been a particularly active participant in AIEE affairs, having served on a number of committees, and written many technical papers.

The coauthor of the insulation article is *L. B. Rademacher*, an engineer under Teague's supervision. Larry is an electrical-engineering graduate of Illinois Institute



of Technology, class of 1943. After a short stint on the Graduate Student Course, Rademacher was assigned to the wartime ordnance engineering section, where he devoted his efforts to development work on various torpedo designs. With the end of the war Rademacher moved over to the more peaceful activity of the Insulation Development Section. Here he tackled many varieties of insulation problems. We should also mention that Teague's educational leanings may be contagious; Rademacher not only attends several night courses sponsored by the Company, but also teaches electrical engineering in Youngstown College.

This is not a stunt to prove that Westinghouse refrigerators operate under water. The compressor units must be tested for leaks. In the new Westinghouse appliance plant at Columbus, Ohio, this is done in the production line by immersing the whole unit in water. Actually this test is made twice—once with the unit charged with air at 200 psi, later, charged with Freon.